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MEMS 411: The Adjustable Bit Brace

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SP21 MEMS 411 Mechanical Engineering Design Project

The Adjustable Bit Brace

This group set out to create an open-source adjustable bit brace as a tool to lower the barrier to entry for smaller individuals looking to pick up tools and work on DIY projects. The brace is designed to highlight 3D printed parts, as well as components that can be fabricated at home by an experienced maker. The design uses standard adjustment mechanisms such as button clips and bolts to bring the bit brace from full size down to 2/3 scale in seconds. The device is advised by engineering models, FEA analysis, stiffness/strength targets, and destructive testing protocols to create a brace that satisfies user needs and predefined performance goals. Several parts were created in an iterative process to determine the best 3D printed design, material, and integration method. The final brace underwent validation proof load testing to ensure that assembly-level analysis was correct and that the brace was safe for operation. With the final addition of steel gussets to the 3D printed components, the brace now exceeds the predetermined strength requirements for functionality. Finally, the brace was used to drill holes into wood beams at several size configurations including the largest and smallest to ensure that functionality and tactile feedback were preserved.

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1 Introduction

Bit braces have many useful applications in wood working including hole depth control, tear out prevention, and safety. Unlike power drills, bit braces allow a user to count applied turns (to make equal depth holes), feel resistance within the material, and prevent splitting in the material. The most common style of bit brace comes with two handles, one designed for the palm to rest on parallel to the ground, and the other to be held with a vertical hand perpendicular to the ground. Figure 1 below shows a typical bit brace. The customer has several complaints about a standard bit brace, and the specific requests and specifications can be found in sections 2.4 and 2.5, respectively. The client would like their bit brace to be compatible with smaller users (specifically their kids) so they have asked for the brace to be able to be scaled down to accommodate smaller users. This scaling has been defined as a decrease in the rotational diameter of the vertical handle and a decrease in the offset height of the top-most horizontal handle. Additionally, the client would like the new bit brace to have a more reliable ratcheting mechanism and a conventional drive fitting to be compatible with an after-market tool holder. Finally, the client would also like the tool to be "Open-Source." They would like all of the constituent parts and assembly techniques to be compatible with a typical "at-home maker" and not require any obscure equipment (such as CNC machines).

2 Problem Understanding

2.1 Existing Devices

There are several existing devices in circulation that accomplish objectives similar to this group's charter, however, they are all missing the adjustable dimensions that are desired by the customer. Generally speaking, the design of the conventional bit brace has not changed greatly since its invention.

2.1.1 Existing Device #1: Fuller Tools Bit Brace [1]

Figure 1: Fuller Tools Bit Brace (Source: Fuller Tools on Amazon)

Link: https://www.amazon.com/Fuller-Tool-890-1072-12-Point-Reversible/dp/B000BDISDC
Model Information: Fuller Tool 890-1072 12-Point Reversible Ratchet Bit Brace Hand Drill with 4-Jaw Chuck
Description: This Fuller Tools Bit Brace features a reversible ratcheting handle mounted onto a 4-jaw chuck. This design has two rotating handles (one on the top and one on the side) that allows the user to plant a drill bit into their work, and turn radially while applying downward pressure. The 4-jaw chuck allows square bits to be held firmly, and the ratcheting mechanism allows the brace to be operated within a reduced envelope.

2.1.2 Existing Device #2: Frylr Hand Crank Drill [2]

Figure 2: Fuller Tools Bit Brace (Source: Fuller Tools on Amazon)

Link: https://www.amazon.com/dp/B078SQTLMM
Model Information: Frylr Hand Drill Speedy Powerful Manual Hand Crank Drill 3/8 inch With S/S cast 3 Jaw Chucks, ABS Anti Slip Handle
Description: The Frylr hand drill features a stick grip and a crank handle attached above a standard 3-jaw chuck. The 3-jaw chuck allows this drill to be compatible with round-shank drill bits, as well as hexagon shank inserts. The chuck-key lets the user apply more gripping friction to the inserted bit. The crank handle works on a gear-tooth system where a bevel gear rotates the user's input torque to rotate the drill bit.

2.1.3 Existing Device #3: Fiskars Crafts DIY Precision Hand Drill [3]

Figure 3: Fuller Tools Bit Brace (Source: Fuller Tools on Amazon)

Link: https://www.amazon.com/Fiskars-Crafts-132420-1001-Precision-Drill/dp/B07MQXNWHQ
Model Information: Fiskars Crafts DIY Precision Hand Drill, Grey, White/Gray
Description: The Fiskars Hand Drill functions with pistol-grip style body and a keyless chuck. This design has an internal gear mechanism connected to the crank handle. The handle can collapse underneath the body and store in a smaller footprint. This design holds smaller drill bits than the Frylr or Fuller manual drills.

2.2 Patents

2.2.1 Albert D. Goodell's Improved Bit-Brace [4] (No. 488,691.)

This is a patent from 1892 for an improved bit brace that allows the user to drill holes by holding the top handle in place and rotating the brace about its vertical axis. The main improvements over older bit braces were an improved ratcheting mechanism and a more durable design. This design is reflective of the Fuller Tools Bit Brace listed in Section 2.1.1.

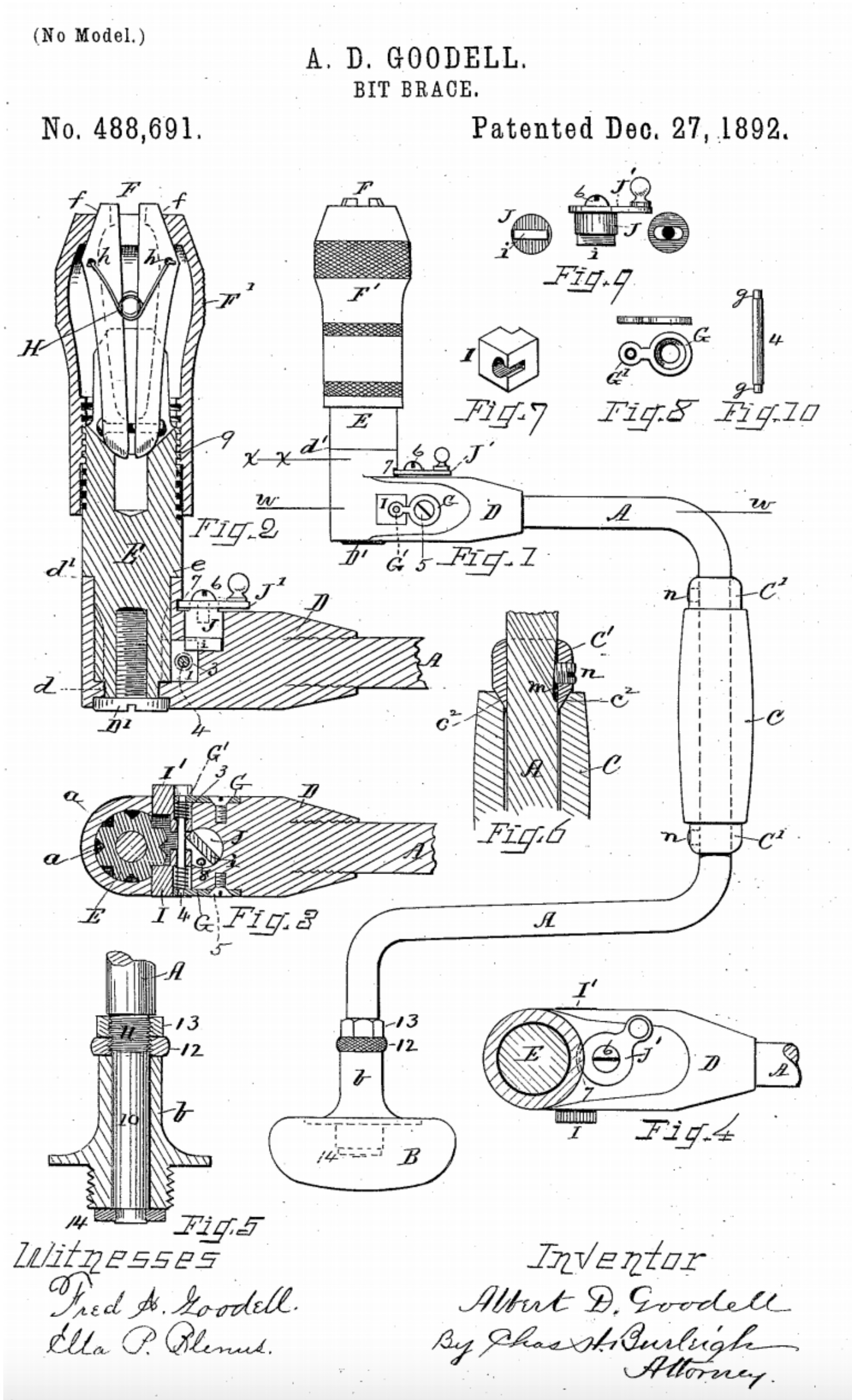


Figure 4: Improved Bit-Brace Patent Schematic

2.2.2 Bit-Brace Chuck [5] (No. 1,593,908.)

This is a 1926 patent for an improved chuck intended to be used with bit braces. The primary purpose of the improved chuck is to improve the sometimes slightly inaccurate alignment of the vertical axis of the brace, which can induce wobbling during operation. The chuck is designed to hold bits with square, round, or tapered shanks.

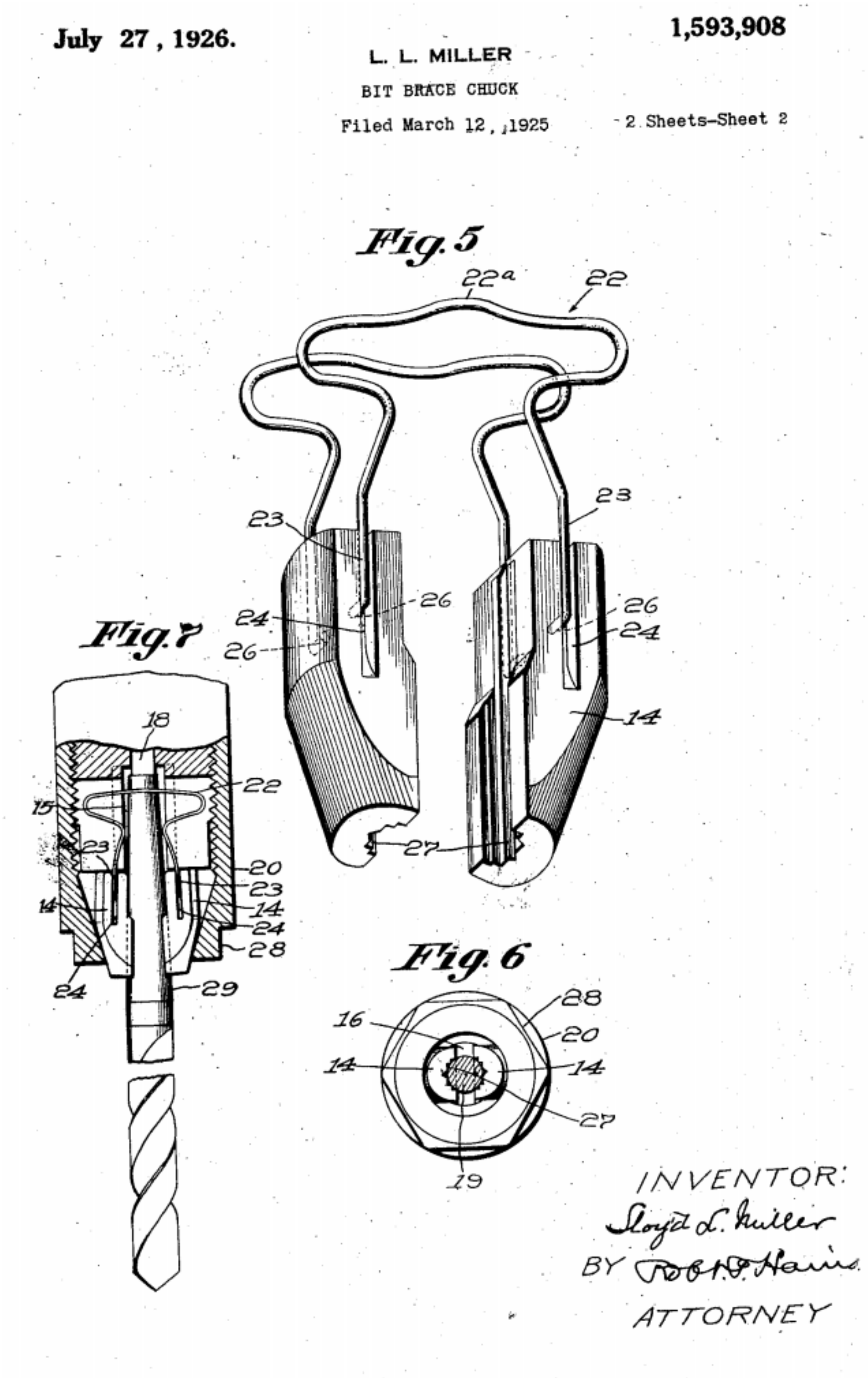


Figure 5: Bit-Brace Chuck Patent Schematic

2.3 Codes & Standards

2.3.1 Hand-held non-electric power tools — Safety requirements — Part 3: Drills and tappers [6] (ISO 11148-3)

This standard from ISO outlines Hand-Held non-electric power tool safety requirements, specifically for drills and tappers. For this group's purpose, this standard outlines general components and safety requirements for non-electric hand drills such as a bit brace or hand-crank drill. Section 4.2.1 "Surfaces, Edges, and Corners" is highlighted as it notes, "Accessible parts of the drills and tappers shall not have sharp edges or angles or rough or abrasive surfaces; see ISO 12100:2010, 6.2.2.1." This specifically applies to the Interpreted Customer Needs in Table 1 where the user indicated they wanted the tool to be safe for use by a maker of any skill level including children.

2.3.2 American Standard Square Drives for Socket Tools Tools [7] (ASA B5.38 - 1958)

The American Standard for Square Drive Socket dimensions outlines the proper exterior dimensions, chamfers, and overall compatibility to be a proper drive. The user expressed that they want the bit brace to be compatible with standard drive chucks, and for the design to be "open-source" so that any maker could recreate this design. Having the bit brace abide by this standard for square drives will allow the design to be compatible with any off-the-shelf attachment.

2.4 User Needs

For the customer interview, Dr. Potter was interviewed to discuss the practical uses for this innovation. The main focus of the conversation was on the background and reasoning behind the adjustment mechanisms. The discussion centered on the need to have the final product maximize safety, prioritize adjustability, and be amenable to amateur maker manufacturing.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Virtual via Zoom; Washington University in St. Louis
Date: February 5^{th}, 2021
Setting: Dr. Potter showed us his current bit brace, as well as some videos of his daughter using the bit brace. We discussed the key use cases and dimensions of the parts, as well as what he wants changed from his current bit brace. We also discussed key load cases, as well as some manufacturing constraints. Lastly we went over some specific off the shelf parts that we can integrate into the design in order to simplify design and manufacturing. The interview was conducted via Zoom and recorded and took an hour.
Interview Notes:
What are the typical uses of the device?

- Drill holes in different materials with a variety of drill bits

What are the current likes and dislikes of the product?

- The feel of the current version is key. Having a one to one relationship between turns of the handle and the turns of the drill bit allows for precise drilling of hole depth and keeps the user connected to the drill bit. The current size of the bit brace is a good size and the materials and finish give a good feel.

- The ratcheting mechanism allows the user to drill in tight locations where a full rotation of the handle is not possible. The current ratcheting mechanism slips under high torques.
- The main downsides of the different available products are the inability for the chuck to interface with a variety of drill bits (only supports square shank, would like it to take in hex and circular shank bits too)
- The current design is too big for Dr. Potter's kids to comfortably use

What is the desired design space?

- The mounting for the chuck and the ratcheting mechanism can be off the shelf (OTS), the majority of the design should be focused on the adjust-ability and feel of the bit brace, as well as selecting a good ratcheting mechanism.

What are the key deliverables?

- The design should be adjustable to allow for a more comfortable use by his kids. It should be easy for a maker to manufacture themselves with 3D printing and hand tools

2.4.2 Interpreted User Needs

Table 1 below outlines a list of interpreted customer needs for the Adjustable Bit Brace (ABB), based on the customer interview. Each interpreted need is ranked on a scale of 1-5 (with 1 being the least important and 5 being the most important) based on the perceived importance of each customer need.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	ABB must be scalable to reduce the height and throw of the main handle	5
2	ABB should be able to be fabricated by a moderately skilled at-home maker without heavy machinery	4
3	ABB's geometry and operation is similar to existing devices	3
4	ABB can operate under the axial and radial loads necessary	5
5	ABB is structural and has minimal deflection	4
6	ABB has a ratchet mechanism and it does not slip	3
7	ABB is lightweight	2
8	ABB accepts all bit shank types	4
9	ABB allows for the user to ascertain the vertical alignment	3
10	ABB is safe to use	3
11	ABB offers tactile resistance during operation	4
12	ABB is easy to adjust with minimal tools	1

After ranking the importance of each customer need we then associate the needs with target specifications that will be referred to throughout the design process.

2.5 Design Metrics

Table 2 below shows the design metrics that will be used to determine the success of the product. The metrics were created by taking the user needs and turning them into measurable deliverables for each aspect of the product.

Table 2: Target Specifications

Metric Number	**Associated Needs**	**Metric**	**Units**	**Acceptable**	**Ideal**
1	1	Adjustability to decrease dimensions from original full-size	Ratio	$\frac{2}{3}$	$\frac{1}{2}$
2	4	Axial load	lbs	> 30	> 45
3	4	Tangential load	lbs	> 15	> 22.5
4	5	Maximum deflection	in	< 0.1	< 0.04
5	4	Ratchet is slip-torque resistant	$in * lbs$	< 71.25	< 106.875
6	7	Total weight	lbs	< 4.5	≈ 2
7	8	Accommodates round, hex, and square shanks	binary	Pass	Pass
8	11	Realistic and manageable resistance	binary	Pass	Pass
9	10	Sharp edges and rough surface check in ISO-11148-3-2012 Section 4.2.1	binary	Pass	Pass
10	7	Square drive specification in ASA B5.38-1958	binary	Pass	Pass

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

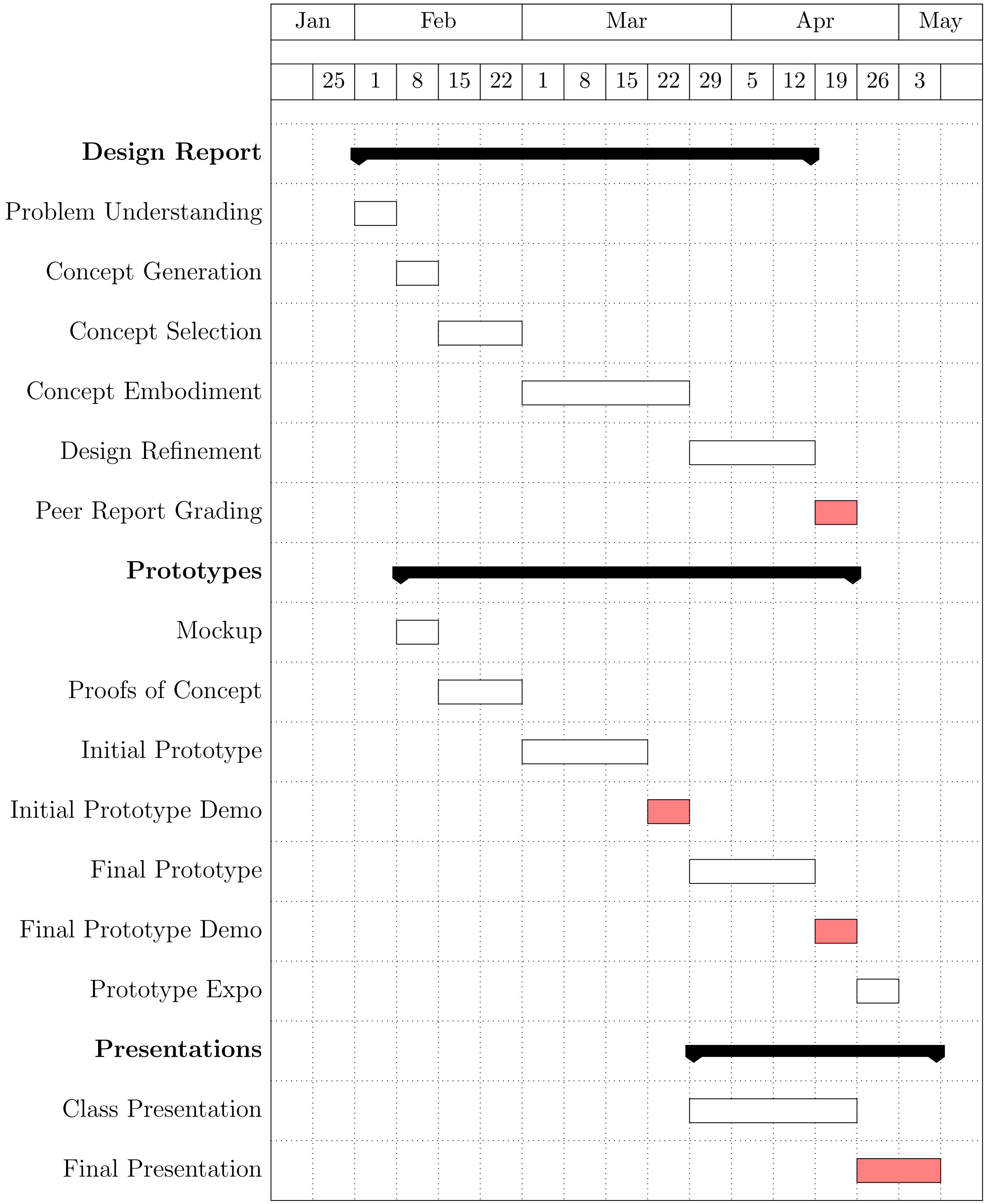


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

The following images are from the ABB mock-up made from cardboard and tape. This mock-up prototype allowed us to analyze all types of rotational movements that we must consider when making the device. We also noticed the importance of having freely moving handles at both the top and the side. This will allow for a much better ergonomic feeling to the device. Along with the overall motion of the device, we noticed that when using the device, it was difficult to keep it steady. This may be due to the simplicity of this prototype, but we now understand that the leveling of the device should be considered. Additionally, aligning the vertical pieces on the top and bottom should be easy such that there is a consistent axis of rotation.

Figure 7 shows the mockup concept in its scaled down or contracted position.

Figure 7: The ABB mockup in its "scaled down" configuration

Figure 8 shows the mockup concept in its scaled up or extended position.

Figure 8: The ABB mockup in its ”scaled up” or extended configuration

Figure 9 shows the mockup concept in its deconstructed configuration where all of the constituent parts are displayed.

Figure 9: The ABB mockup deconstructed

3.2 Functional Decomposition

Figure 10 depicts the functional decomposition of the Adjustable Bit Brace. The overall function of the ABB is listed on the left hand side of the function tree, with successive functions branched off to the right.

- Manual Drill Driver
  - Rotates and drills holes
  - Scaled vertical grip distance
  - Scaled rotational throw
  - Bubble level readout
  - Accepts square drive attachment tools

Figure 10: Function Tree for ABB, coded with tikz

3.3 Morphological Chart

The following figure shows is a morphological chart for the ABB that offers visualization of each sub-function from the function tree (Fig. 11). The drawings in this chart shows different ideas on how we could accomplish each specific sub-function.

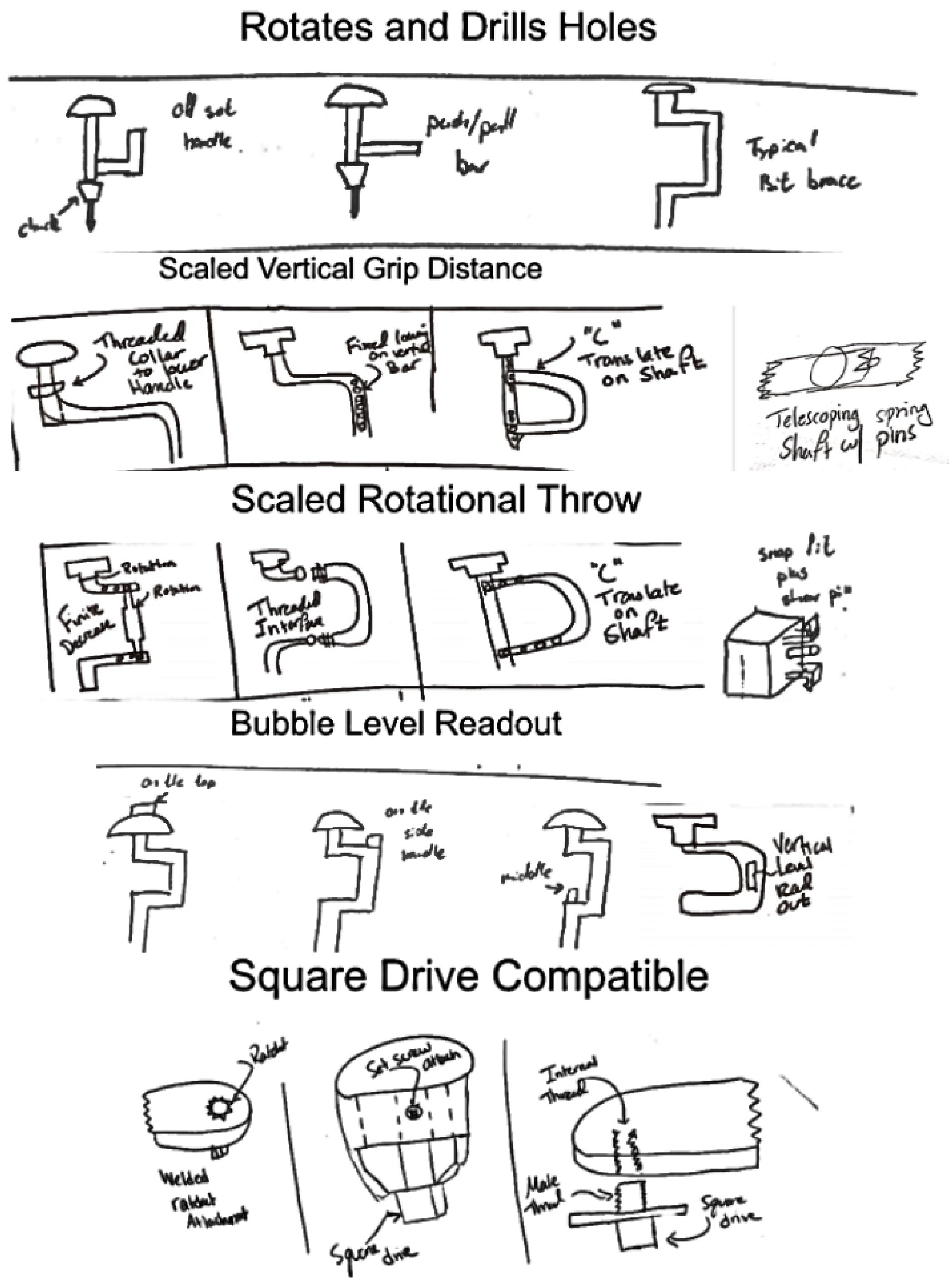


Figure 11: Morphological Chart for ABB

3.4 Alternative Design Concepts

3.4.1 Lego Bit Brace

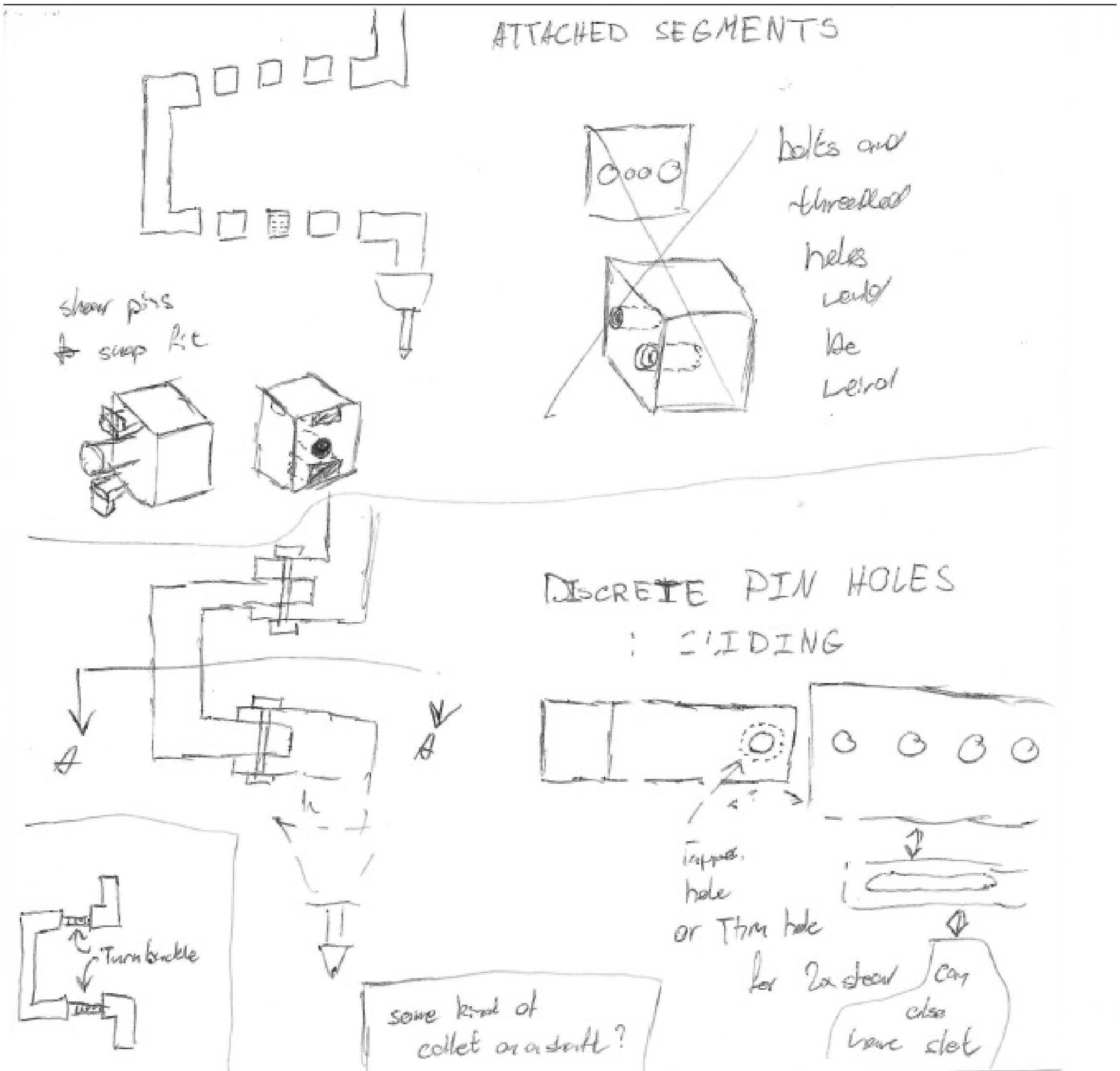


Figure 12: Preliminary sketches of the Lego bit brace and other initial concepts

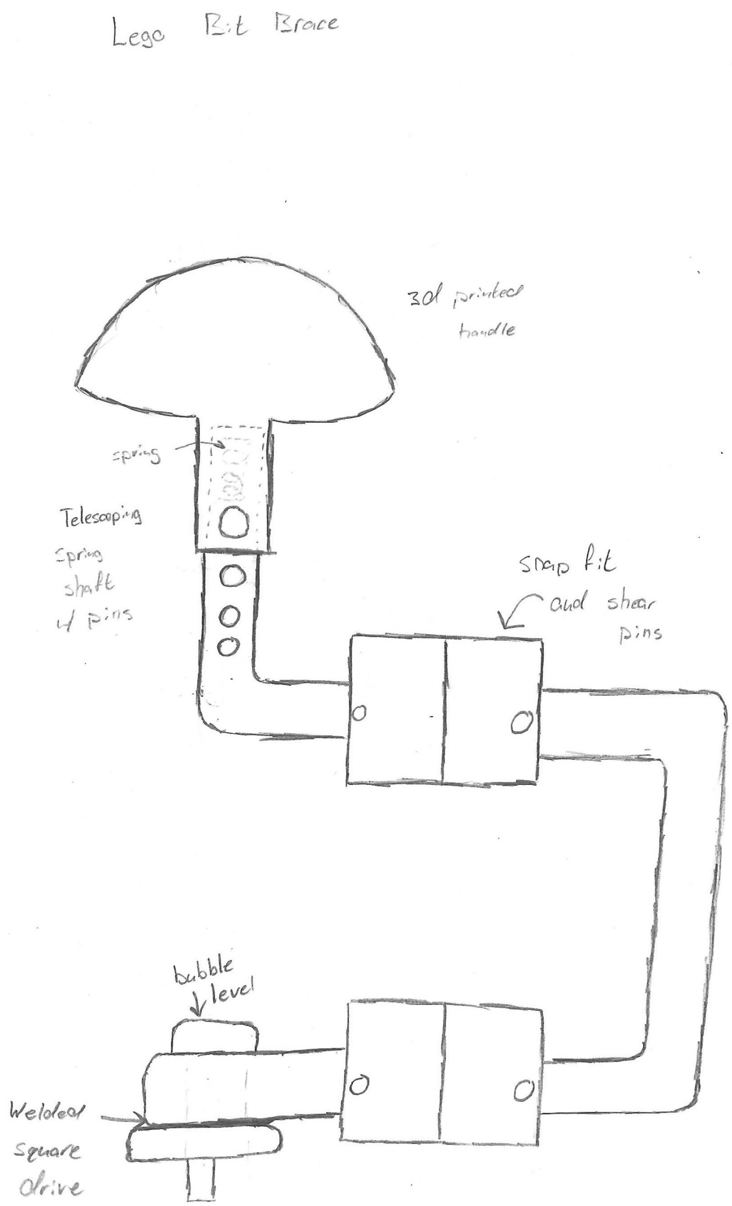


Figure 13: Final sketches of the Lego Bit Brace

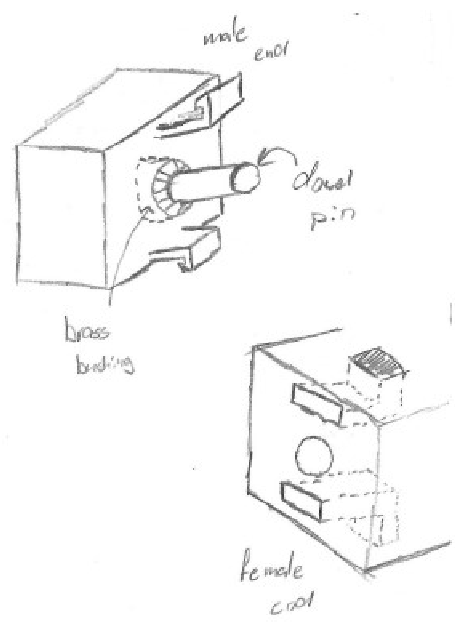


Figure 14: Detailed view of the Lego Blocks for the Lego Bit Brace

Description: The Lego Bit Brace has two methods of finite adjustment. The vertical movement is controlled with a pin and telescoping shaft. In order to improve the feel of the telescoping shaft, a spring is hidden inside the handle and is used to aid in the movement of the shafts. The key design feature on the Lego Bit Brace is the attachment blocks used to adjust the rotation of the device. The 3D printed blocks snap together using snap hooks and grooves. In order to support the loads through the device, off-the-shelf bushings and shear pins are pressed into the blocks and will take a majority of the vertical and torsional loads into the blocks.

3.4.2 C-Bar Brace

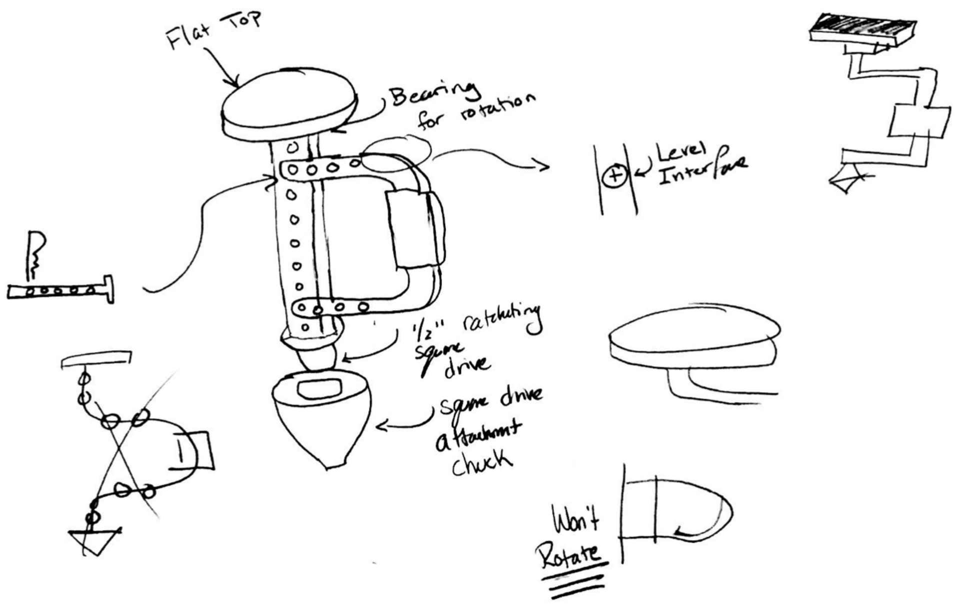


Figure 15: Preliminary sketches of the C-Bar Brace Concept of the ABB

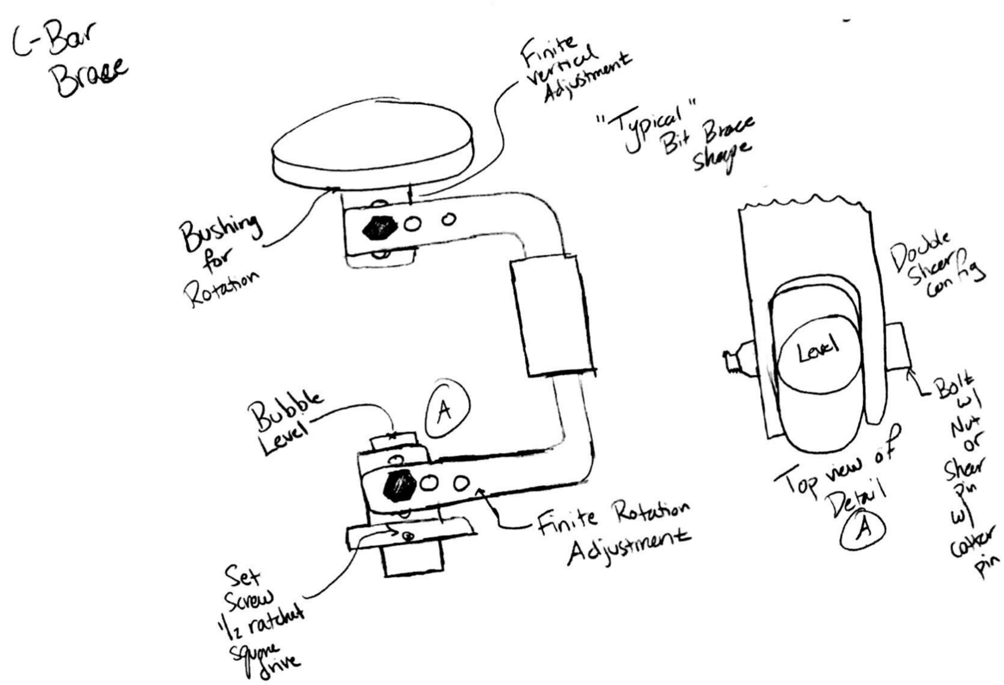


Figure 16: Final sketches of the C-Bar Brace Concept of the ABB

Description: The C-Bar Bit Brace employs a flat top handle design and perpendicular vertical grip to create a "standard" or "typical" bit brace shape. The design features a set-screw attachment square drive socket to abide by the customer need of being multi-drill bit compatible. Additionally, the design features a bubble level in the bottom quadrant of the brace where the user can look down and ensure that their hole will be drilled square to the surface of interest. Finally, the design uses a "C-bar finite adjustable interface" where the brace is composed of three separate pieces, attached using double shear clevis mechanisms. This provides both the vertical and rotational scaling desired by the customer.

3.4.3 Turnbuckle Adjustment Bit Brace

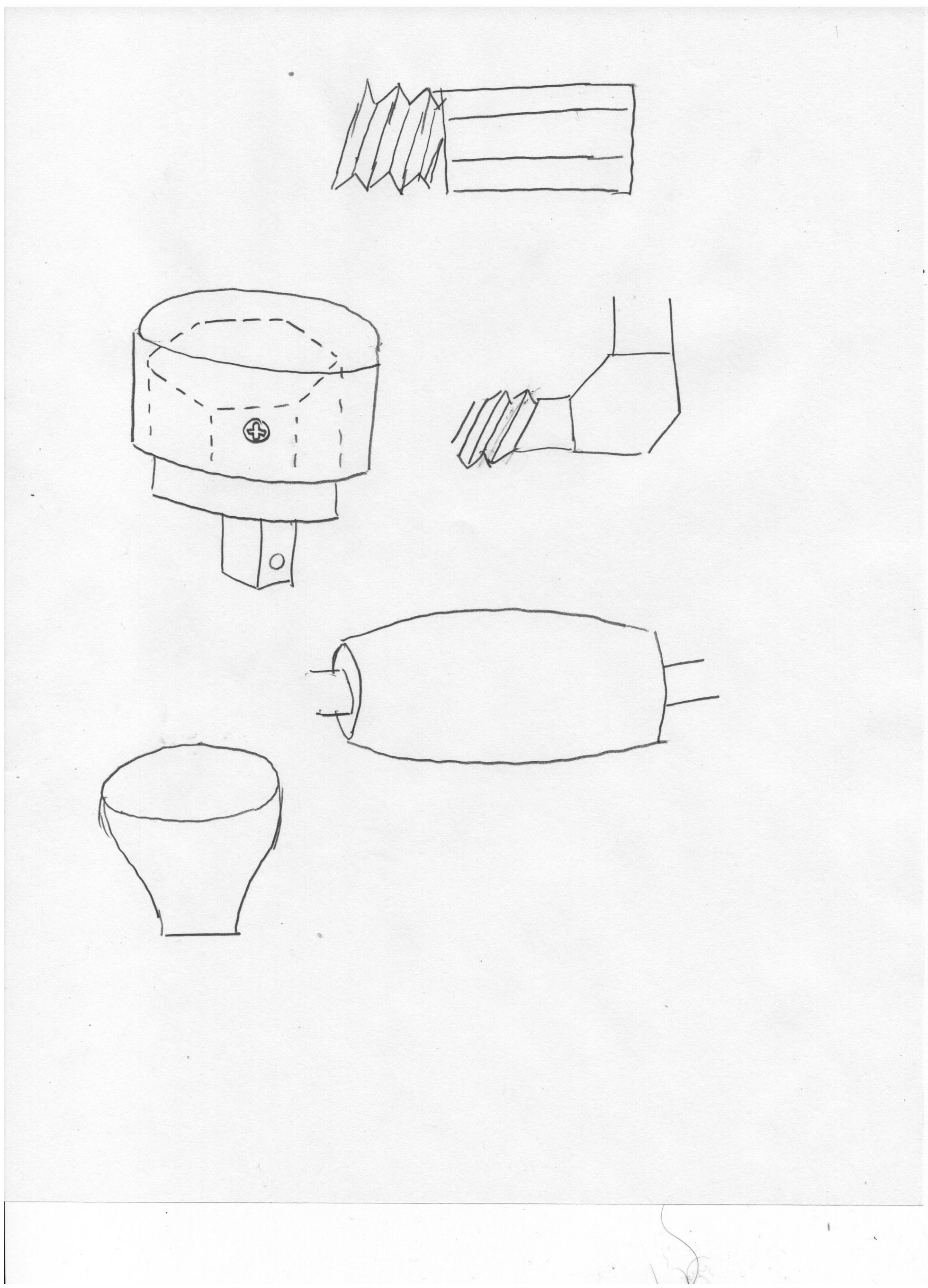


Figure 17: Preliminary sketches of the Telescope Adjustment of the ABB

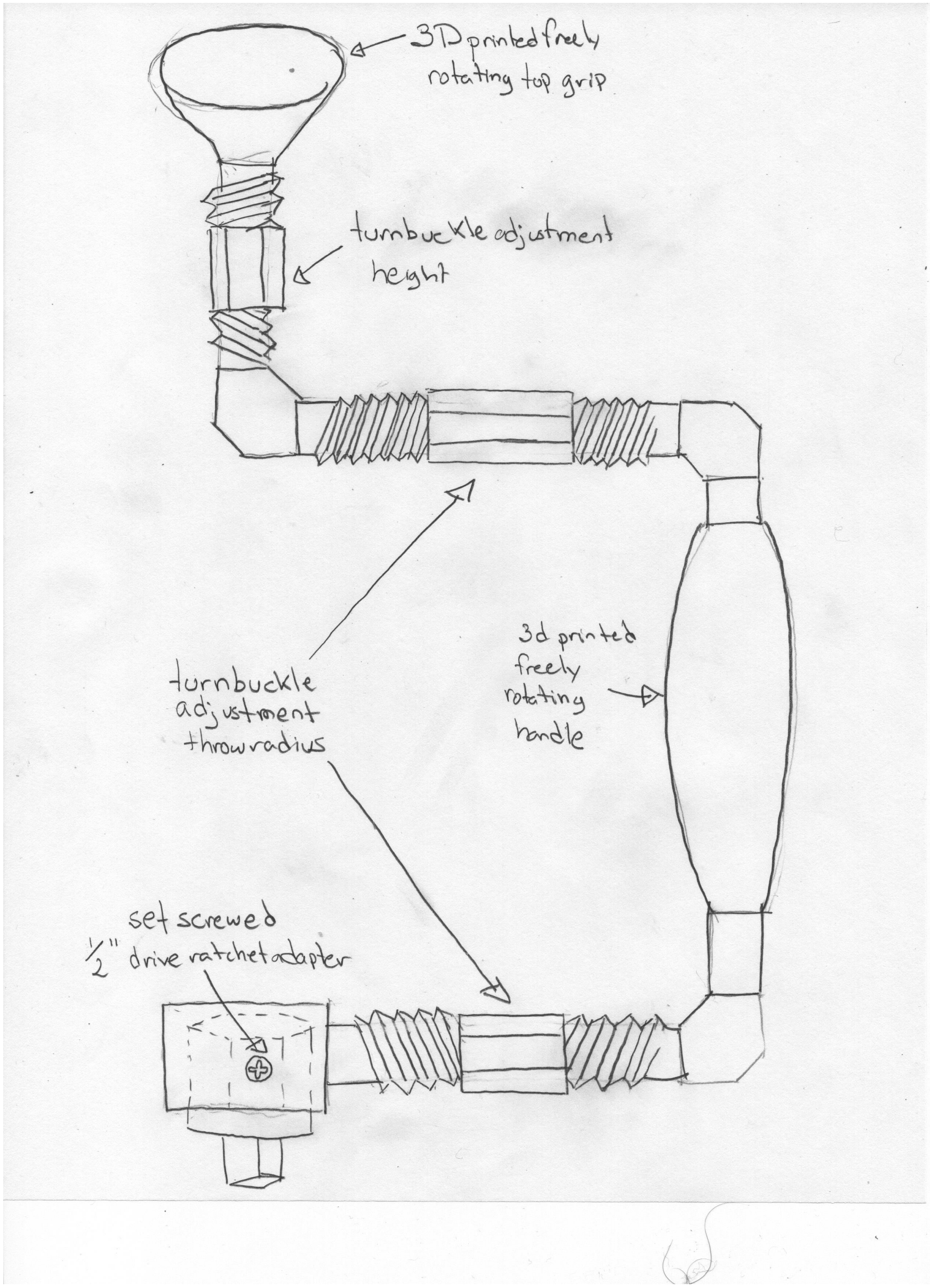


Figure 18: Preliminary sketches of the Telescope Adjustment of the ABB

Description: The Telescope Adjustable Bit Brace uses a turnbuckle-style length adjustment to change both the radius of rotation and the height of the top handle. Two horizontal turnbuckles are used in tandem for the radius, while a single vertical turnbuckle adjusts the height. Turnbuckle adjustment allows for infinite adjustability within the entire range.The top grip and center handle are 3D printed parts that are free to rotate on their axis. There is a ratcheting half-inch drive attachment set screwed to the bottom of the bit brace.

3.4.4 Telescopic Bit Brace

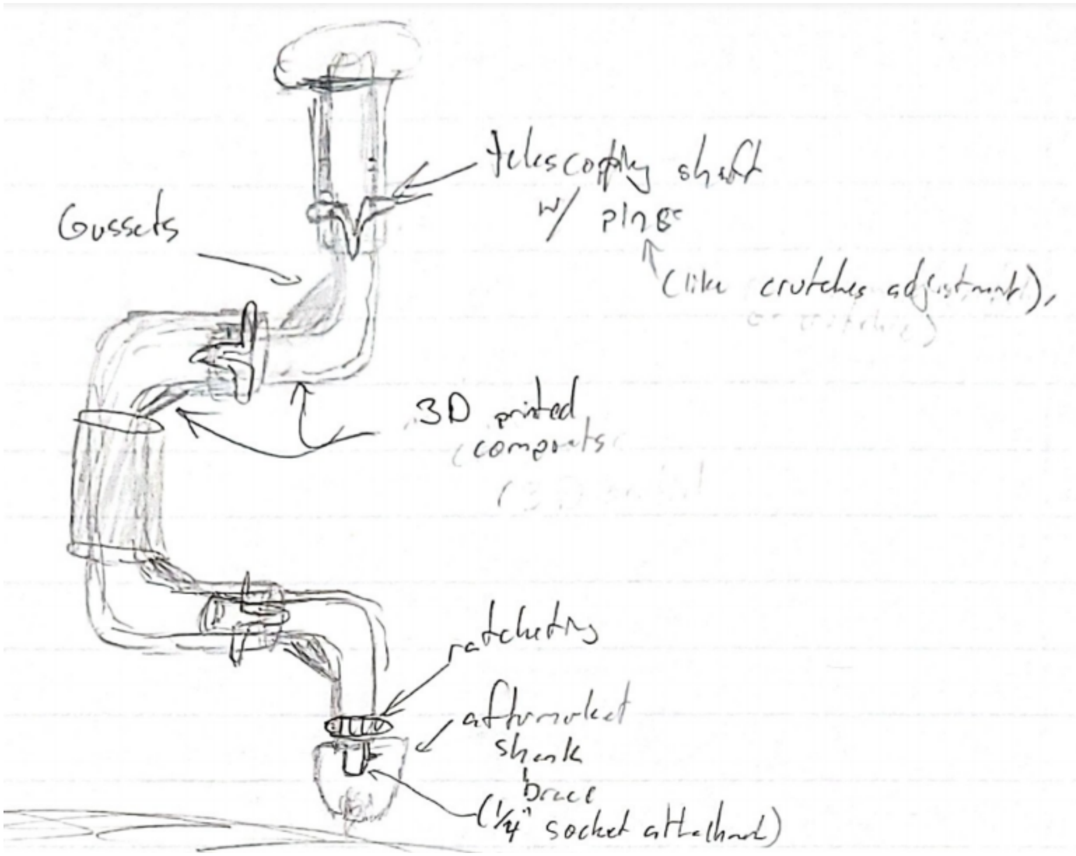


Figure 19: Preliminary sketches of the Telescopic Brace Concept of the ABB

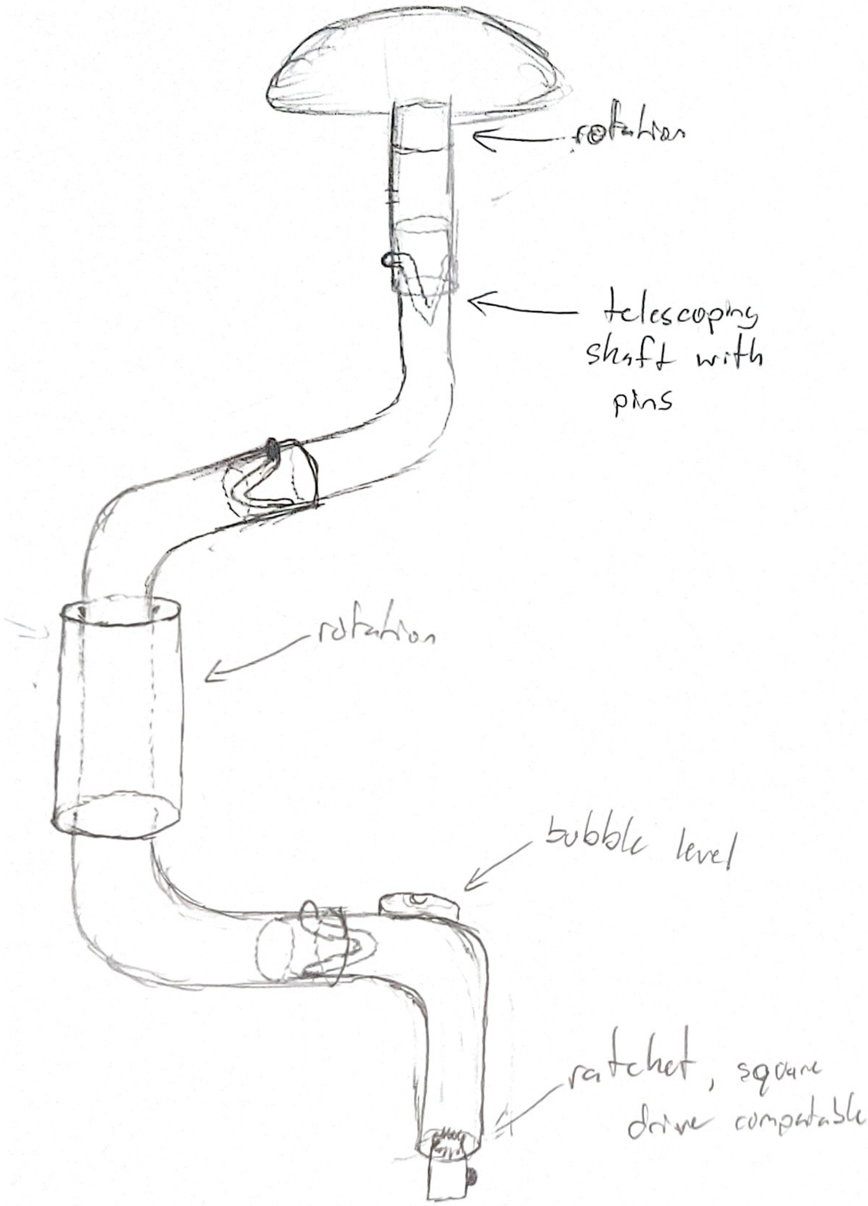


Figure 20: Final sketch of the Telescopic Brace Concept of the ABB

Description: This concept for the Adjustable Bit Brace (ABB) includes adjustable telescoping shafts that are linked together with pin clips inside of the tubes. The clips are similar to those that are inside of adjustable crutches. This allows for both vertical and rotational throw scaling from original size to a decreased size. The ABB will operate similar to typical bit braces with an included ratcheting mechanism at the base with a fixed square drive connection. The Telescopic Brace concept also includes a bubble level for leveling the ABB throughout drilling. There are also 2 handles, one at the top and one on the side, to allow rotational movement.

4 Concept Selection

4.1 Selection Criteria

The figure below shows the analytical hierarchy process matrix that was used in the concept selection process. The key factors considered were the safety of the brace, the quality, effectiveness, and reliability of the vertical adjustment method, the quality, effectiveness, and reliability of the radial adjustment, the accessibility of fabrication by an experienced at-home maker, and the overall stiffness of the device (as an indicator of reliable operation).

	Safety	Vertical Adjustment	Radial Throw Adjustment	Accessibility of Fabrication	Stiffness	Row Total	Weight Value	Weight (%)
Safety	**1.00**	3.00	3.00	3.00	5.00	15.00	0.36	35.66
Vertical Adjustment	0.33	**1.00**	5.00	3.00	0.33	9.67	0.23	22.98
Radial Throw Adjustment	0.33	0.20	**1.00**	3.00	0.33	4.87	0.12	11.57
Accessibility of Fabrication	0.33	0.33	0.33	**1.00**	0.33	2.33	0.06	5.55
Stiffness	0.20	3.00	3.00	3.00	**1.00**	10.20	0.24	24.25
					Column Total:	**42.07**	**1.00**	**100.00**

Figure 21: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

The figure below shows the weighted scoring matrix used in the ABB concept selection process. The four design concepts considered were the LEGO Bit Brace, the Telescopic Bit Brace, the C-Bar Bit Brace, and the Turn Buckle Bit Brace.

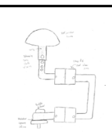
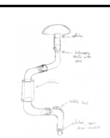
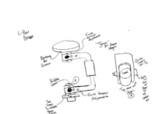
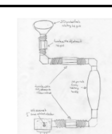
Alternative Deisgn Concepts		**LEGO Bit Brace**		**Telescopic Bit Brace**		**C-Bar Bit Brace**		**Turn Buckle Bit Brace**	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Safety	35.66	1	0.36	5	1.78	1	0.36	5	1.78
Vertical Adjustment	22.98	5	1.15	5	1.15	3	0.69	4	0.92
Radial Throw Adjustment	11.57	3	0.35	5	0.58	3	0.35	1	0.12
Accessibility of Fabrication	5.55	4	0.22	3	0.17	2	0.11	5	0.28
Stiffness	24.25	1	0.24	2	0.48	1	0.24	3	0.73
	Total score	**2.317**		**4.162**		**1.746**		**3.823**	
	Rank	**3**		**1**		**4**		**2**	

Figure 22: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

The telescopic bit brace design concept scored amongst the highest concepts for safety since we deemed the adjustment mechanism and overall design to be much safer than other design concepts. The proposed adjustment mechanism is similar to that of crutches and telescoping pool equipment, which are safe pieces of equipment themselves, so we can conclude this alternative design is also safe. Vertical and radial adjustments were of the top priority when considering alternative design concepts. The telescopic bit brace design scored in the highest ranking for both of these selection criteria due to the ease of adjustment and the range of adjustment that is allowed. The telescopic bit brace did not score as high in the accessibility of fabrication criterion since the concept is much harder to make as compared to some of the other concepts. There are a lot of inter-working parts that need to all come together into one cohesive part, which makes the accessibility of fabrication not score as highly as other design concepts. The telescopic bit brace is the second-best design concept when it comes to stiffness, which is the final selection criterion considered. This concept is not the best in terms of stiffness since telescoping tubes have clearances between the tubing that may cause the overall device to wiggle a little. The turnbuckle bit brace is much stiffer in its adjustment areas, which caused that design to score higher in the stiffness category.

4.4 Engineering Models/Relationships

4.4.1 Model 1: Torsion on a Hollow Shaft [8]

One potential method of failure is torsion of the thin walled hollow tubes. The figure below shows the calculations of the wall stress for a cylinder in torsion:

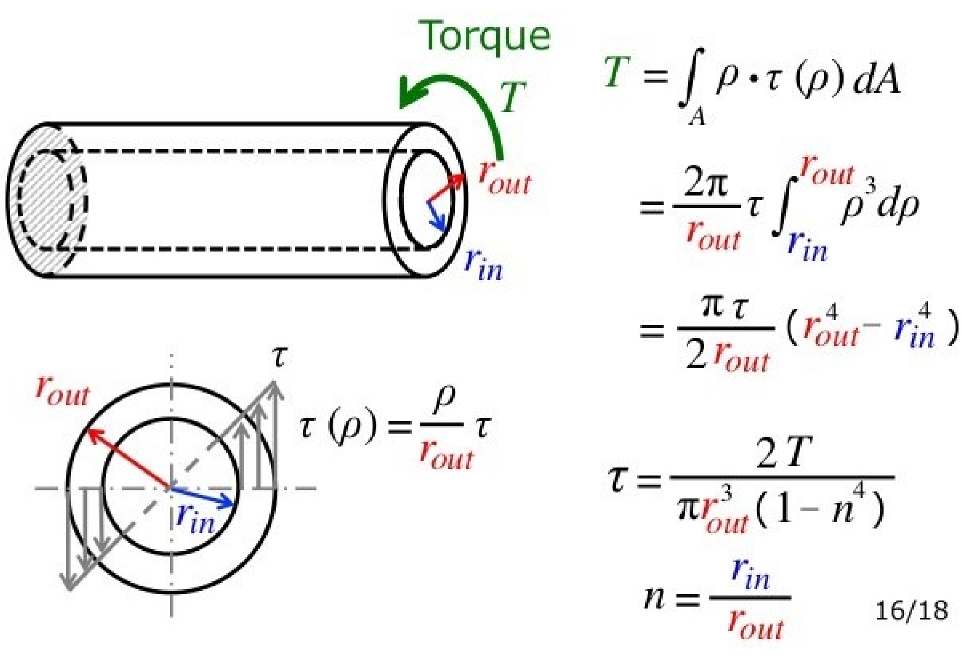


Figure 23: Hollow cylindrical tube in torsion

Where T is the applied torque, r_{out} and r_{in} are the outer and inner radii, τ is the shear stress, and ρ is the integrating variable. This model will be helpful for analysis of the telescoping tubes used in the adjustment mechanism to ensure that they will not fail under high resistance during operation.

4.4.2 Model 2: Shear Failure on a pin [9]

One potential method of failure of the adjustment mechanics of the Bit brace is either a double shear failure of a pin or a single shear failure on a button clip. This model will be helpful in sizing the button clip adjustment fastener during part selection.

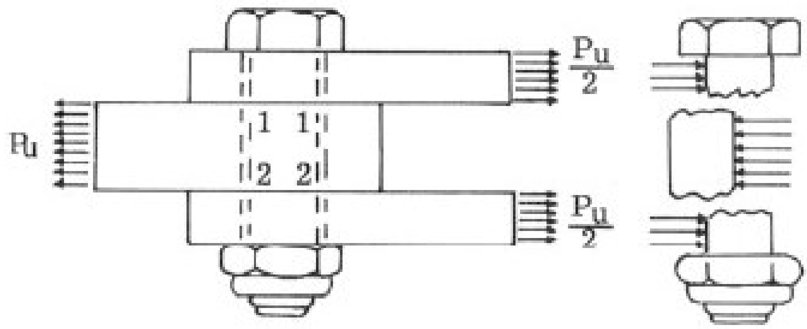


Figure 24: Image of a bolt failing in double shear

Where P_u is the ultimate load at which the bolt will fail, and sections one and two are the sections where the bolt fails at. The image above shows a bolt loaded in double shear, where the ultimate load in shear can be determined by the equation below,

$$P_u = 2\tau_{us}A_s$$

Where $\tau_u s$ is the ultimate shear strength, and A_s is the cross section of the bolt.

For single shear, the failure mode is the same, however the ultimate load is halved, and can be shown by the equation below.

$$P_u = \tau_{us}A_s$$

4.4.3 Model 3: Reduced Radius of Revolution

This model outlines the relative radii of rotation for the ABB as it is being designed to scale down. This model is useful in design as a quick reference to ensure that the adjustment method is sufficient to match the customer's expectations and needs. The η factor offers a quick conversion from a starting radius to a final radius, or a quick inspection of a growth factor to ensure that the starting radius will remain sufficient. The model is governed by the relationship between the circumference (and consequently, the radii) of the different circles of rotations:

$$C_{outer} = 2 * \pi * R$$

$$C_{inner} = 2 * \pi * r$$

Where C_{outer} is the circumference of the rotation of the bit brace at the fully extended configuration, R is the radius of the ABB at its fully extended configuration, C_{inner} is the circumference of the rotation of the bit brace at the fully condensed configuration, and r is the radius of the ABB at the fully reduced configuration. Per the customer interview:

$$\eta_{want} = \frac{C_{inner}}{C_{outer}} = \frac{r}{R} = \frac{1}{2}$$

$$\eta_{need} = \frac{C_{inner}}{C_{outer}} = \frac{r}{R} = \frac{2}{3}$$

Where η_{want} is the relative radius factor given the customer's ideal result for the design, and η_{need} is the minimum acceptable radius reduction as outlined in the Table of Customer Needs.

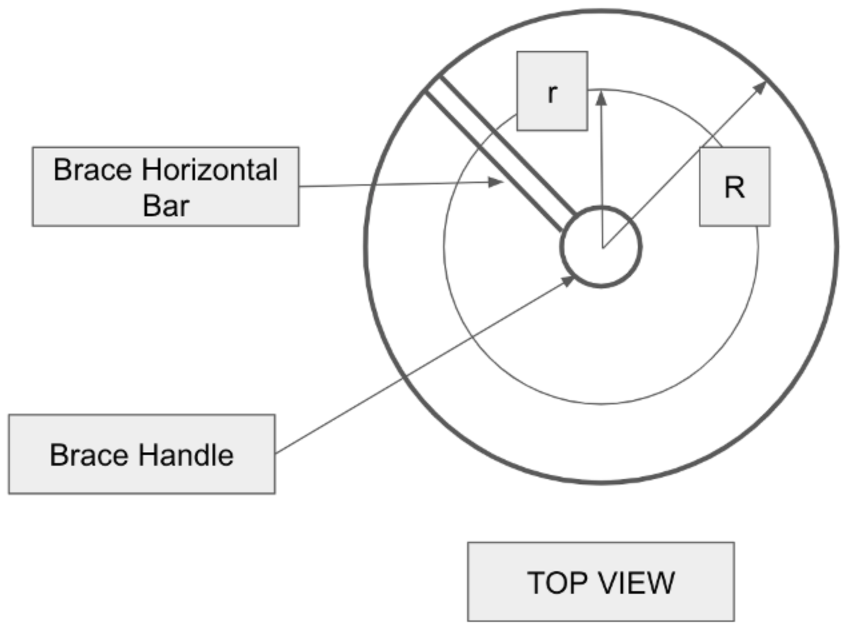


Figure 25: A schematic of the relative radii of rotation for the ABB

5 Concept Embodiment

5.1 Initial Embodiment

The figures below show drawings of the initial CAD prototype of the Adjustable Bit Brace. The drawings include the a three view drawing of the bit brace in its fully extended configuration, a three view drawing of the bit brace in its fully contracted configuration, an isometric view with bill of materials, and an exploded view with balloons identifying components from the bill.

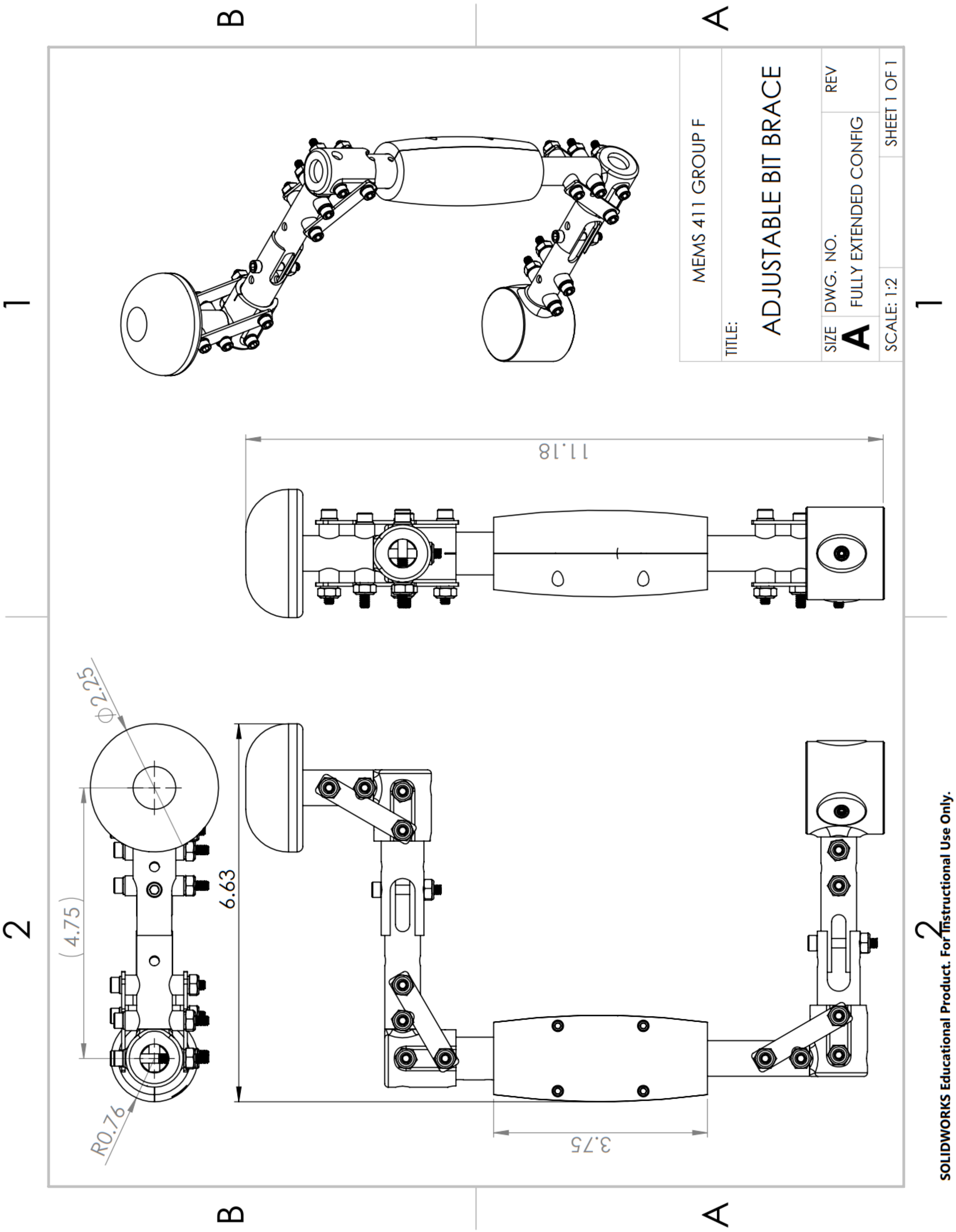


Figure 26: Assembled Bit Brace Extended Configuration with overall dimensions

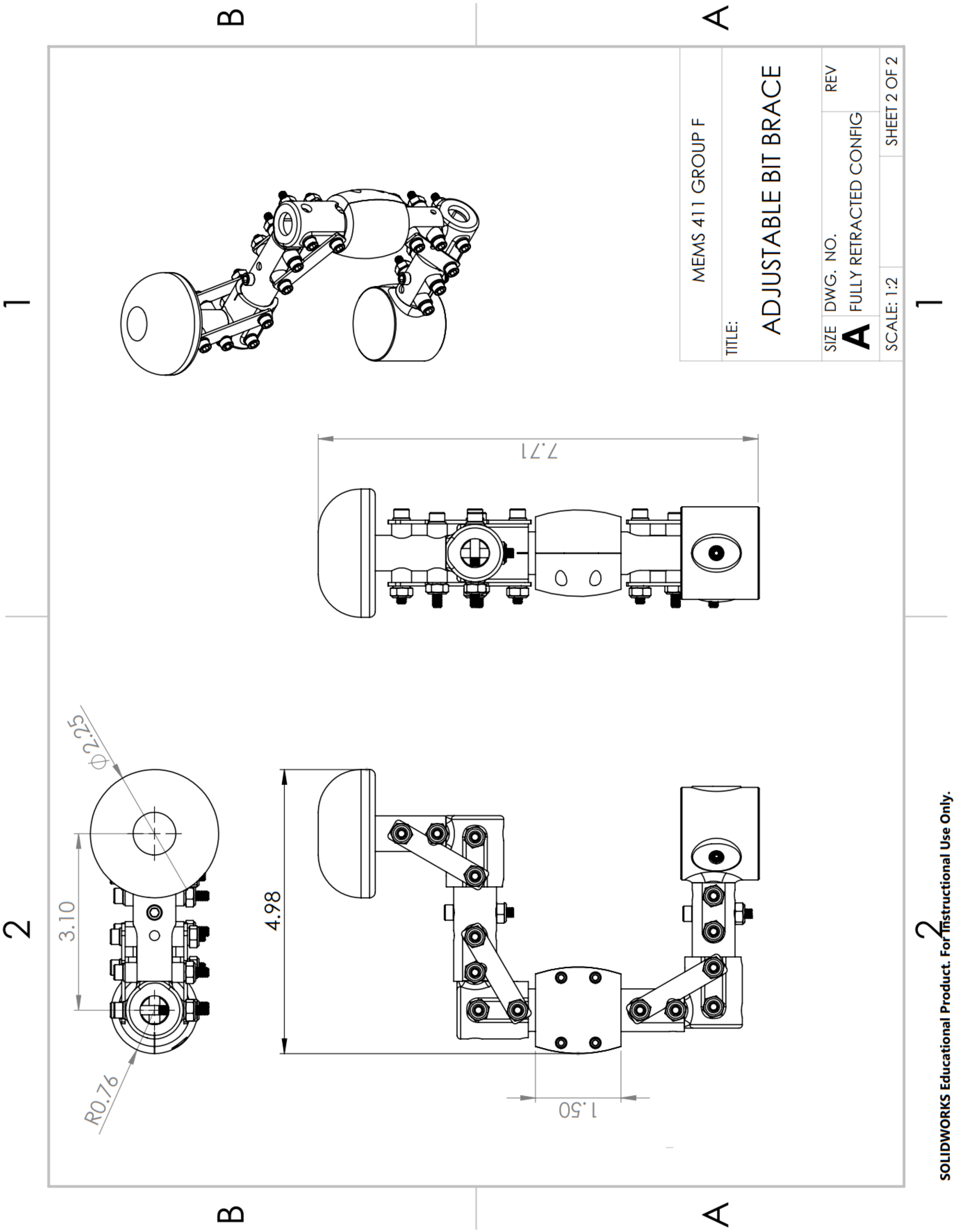
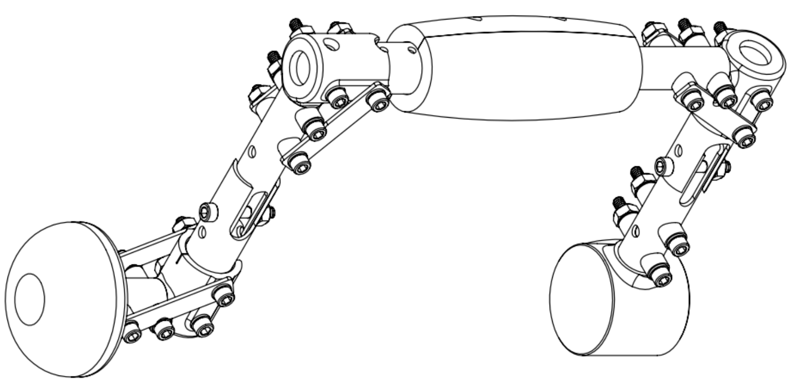


Figure 27: Assembled Bit Brace Contracted Configuration with overall dimensions



BOM Table

ITEM NO.	PART NUMBER/DESCRIPTION	QTY.
1	TopBracket	3
2	.75 Vertical Tube	1
3	.625 Vertical Tube	1
4	RatchetingFixture	1
5	Saddle Washer	16
6	.625 Horizontal Tube	1
7	.75 Horizontal Tube	1
8	Gusset Brace	6
9	94282A411	1
10	.625 Lower Horizontal Tube	1
11	.75 Lower Horizontal Tube	1
12	Left Vertical Handle Tall	1
13	Right Vertical Handle Tall	1
14	91251A203	2
15	92394A112	4
16	91251A107	4
17	91251A203	14
18	5360N123	28
19	90633A009	16
20	92394A114	2
21	92311A192	2
22	Top Handle	1
23	6338K312	1
24	top top tube	1

WASHINGTON UNIVERSITY IN ST LOUIS

TITLE: BIT BRACE WITH BOM

PREPARED BY: A. LEVY — DATE: 03/29/2021

REVIEWED BY: D. LUBERDA — DATE: 03/29/2021

THIRD ANGLE PROJECTION

SIZE B — DWG. NO. — REV

SCALE 1:2 — SHEET 1 OF 2

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND TOLERANCES ARE: DECIMALS .X ± .1 .XX ± .01 .XXX ± .005

Figure 28: Assembled isometric view with bill of materials (BOM)

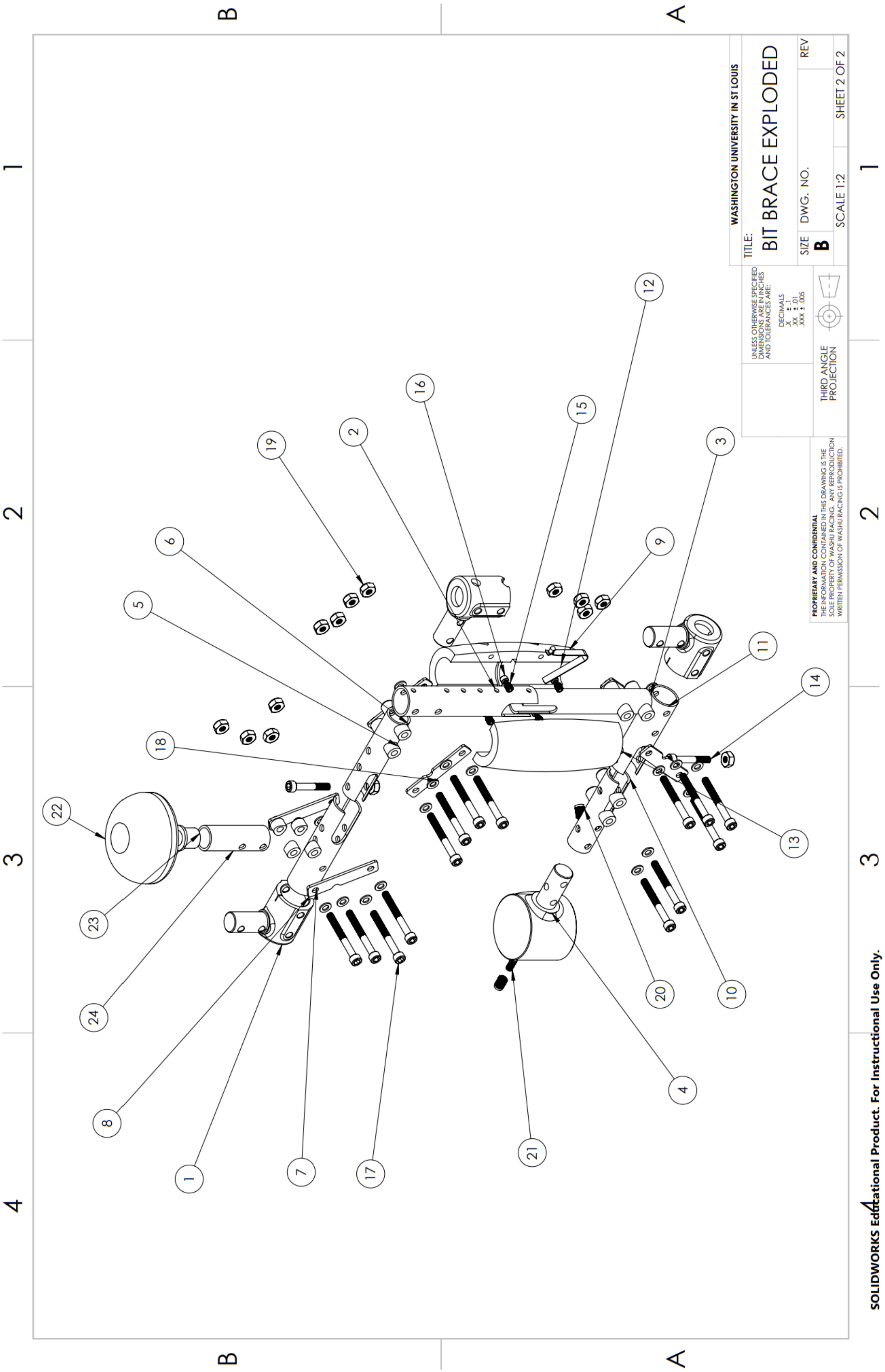


Figure 29: Exploded view with callout to BOM

5.2 Performance Goals

The prototype performance goals identified by the group are:

1. **The bit brace is able to be fabricated by a reasonably skilled at-home maker with access to light-duty machinery such as belt sanders, hand tools, and 3D printers.**
2. **The bit brace is able to withstand > 30lbs of vertical force; > 15lbs of tangential force while enduring less than 0.1" of vertical deflection**
3. **The bit brace should be able to accomplish goal 2 in its full size configuration and at a reduced configuration of 2/3 the original dimensions**

5.3 Proofs-of-Concept

The Proof-of-Concept period of the design of the bit brace was very important in advising the joints between different sections of the brace. The main objective of our group was to rapidly prototype and test components due to the ease of assembly and manufacturing. The testing was done on PLA prototypes of the final components. This testing demonstrated that the tolerances used to constrain the aluminium tubing on both the OD and the ID of the tube were sufficient, however it demonstrated that using PLA would not be sufficient due to the inherent weakness of the printed components between each printed layer. The figures below shows the testing setup used for the FDM components, as well as the associated failure of the FDM Part.

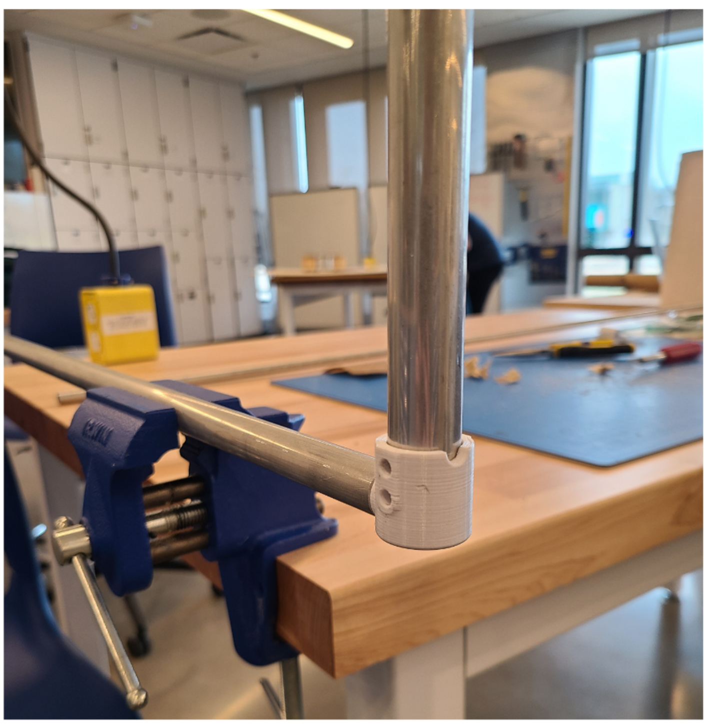


Figure 30: The Proof of Concept Testing Setup

Figure 31 below shows the failed PLA part.

Figure 31: The Failed Component After Testing

This testing changed our manufacturing goal to using SLA 3D printing, as SLA resin printing is significantly stronger and more isotropic than FDM parts. Not only will this stiffen our final product, but it will also avoid premature failure between the layers of an FDM part

We then preformed FEA on the SLA printed part, and 32 below shows that the SLA component will fail at the same location as the PLA. In order to maintain adjustability in the bit brace, we decided to instead support the bracket with gussets instead of continuing to modify the printed component.

The figure below shows the FEA results from simulating the component out of SLA.

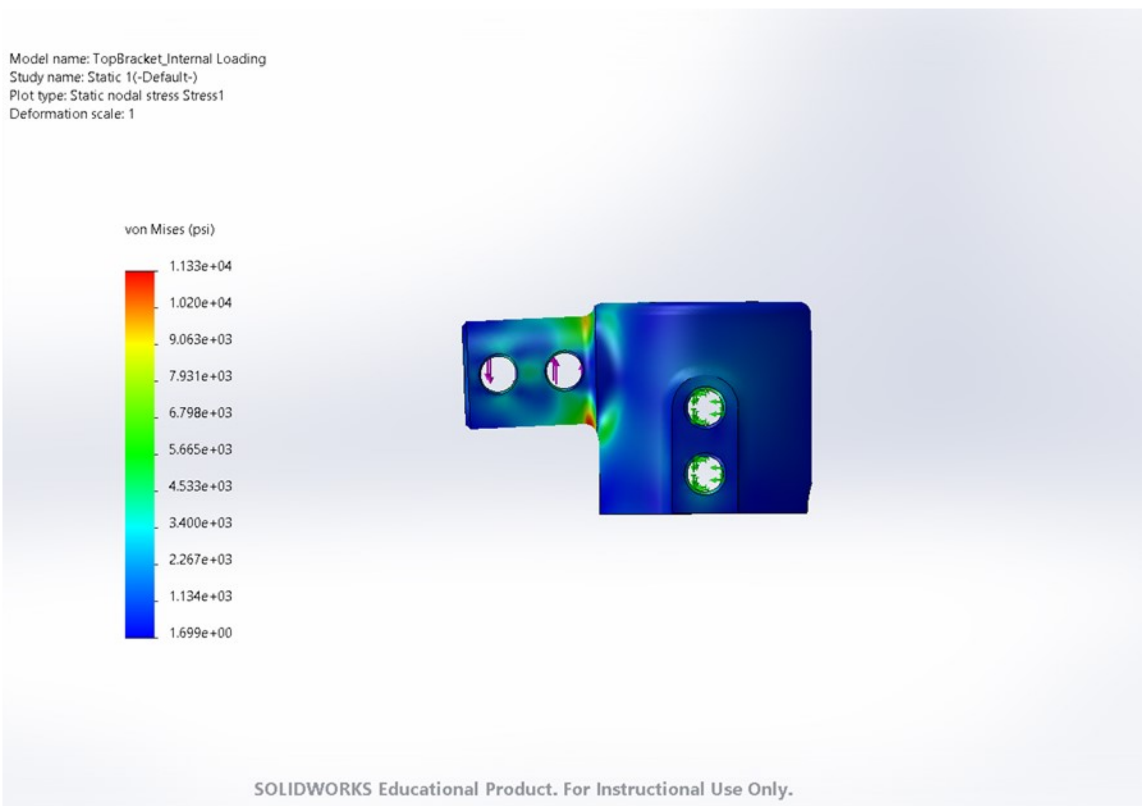


Figure 32: FEA Simulation Results for the Top Bracket

The figure below shows the final SLA printed component.

Figure 33: Final Revised Component post testing and FEA

This has ended up as a modified version of the selected concept: The Telescopic Bit Brace. The design continues to use the 3D printed elbow brackets, however, it uses a different adjustment mechanisms. The team was unable to fit button clips in the horizontal adjustment due to the short lengths of the horizontal tubes in the contracted configuration. The design also employs external steel gussets that bolt onto the outside of the SLA printed brackets. This is a deviation from the original concept that had an internal gusset as shown in Figure 19 of Section 4, or no gusset as shown in Figure 20 of Section 4.

6 Design Refinement

6.1 Model Based Design Rational

6.1.1 Material Selection and Tube Width

The first question we encountered when designing the brace was what material and tube size should be used when building the prototypes. In order to solve this problem, we created a simplified model of the bit brace that was designed out of one piece of homogeneous metal. This allowed us to quickly simulate the deflections on different materials and tube sizes with the design loads. Below is one image of the stress plot on the simplified model.

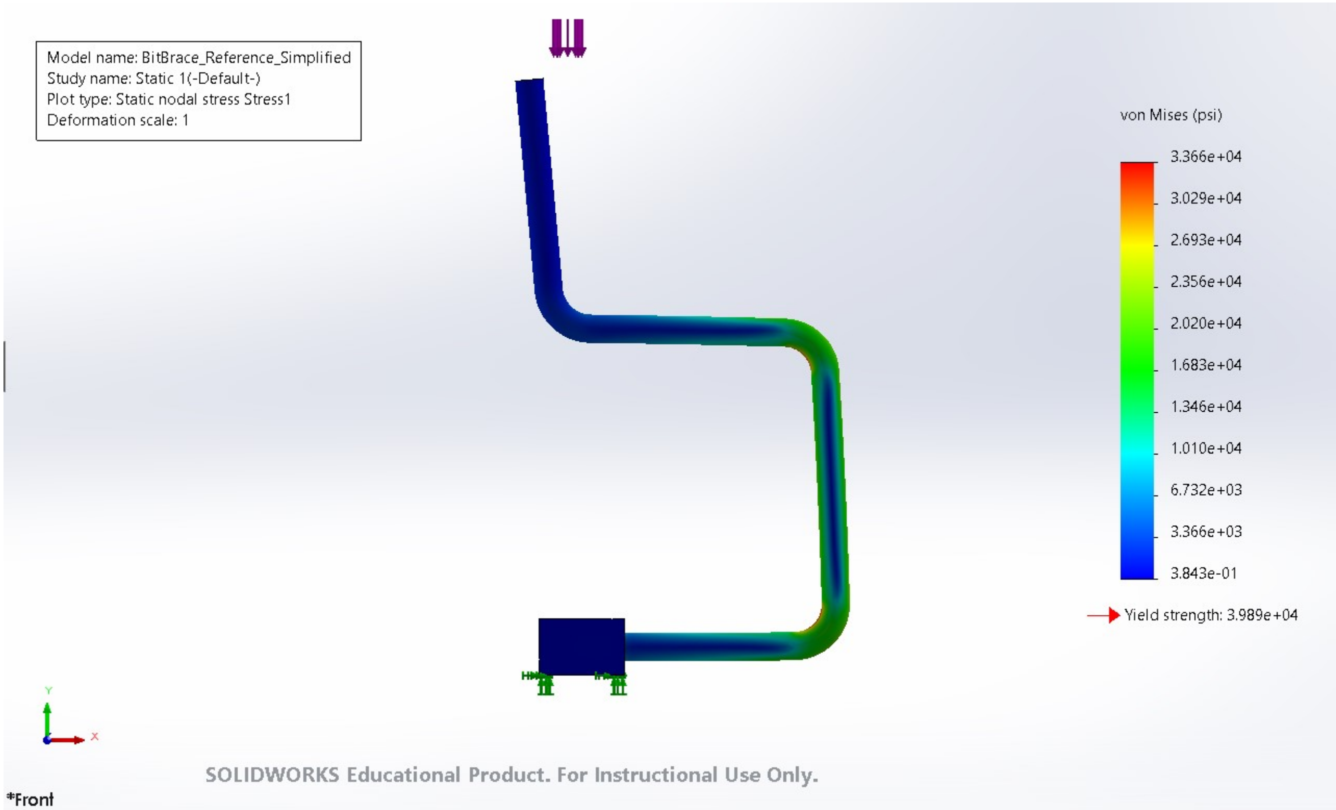


Figure 34: Simplified ABB FEA

By rapidly simulating different tube sizes and materials, we decided on using 6061 Aluminium with an 0.058" wall thickness as our minimum tube size. This allowed us to start cadding the rest of the fixtures and joints in the brace now that we knew that our selection of tubes would not fail under the design loads. The assumption here was that we knew the brace would be made of tubes as thick and thicker than 0.058" so if the entire brace survives at this minimum thickness then the design is okay. The model used here is Finite Element Analysis of the brace with a fixed bottom end and a vertical load of 30lbs applied at the top. This is meant to represent a drill bit being constrained by a hole during operation and a load applied by the user at the top end. The results are presented as the von Mises stress in PSI. The final stress value is presented on the color scale as less than the final yield value of the material.

6.1.2 Implementation of Gussets

After deciding on the minimal required tube size, we started to focus on the design of the 3D Printed Joints. The FEA on the simplified Bit Brace showed us that the major stress concentrations on the part would occur at the inside of each bend, therefore we would need to focus our efforts on making sure that the elbow brackets we designed would not fail. We chose to print the elbow brackets on the SLA Resin printer, as those printed parts are solid and significantly more homogeneous than the FDM alternative. Before running FEA on the bracket, we drew a free body diagram of the upper portion of the bit brace in order to determine the force distribution on the bolt holes of the elbow bracket. The figure below shows a sketch of the bit brace and the corresponding free body diagram, with associated reaction loads.

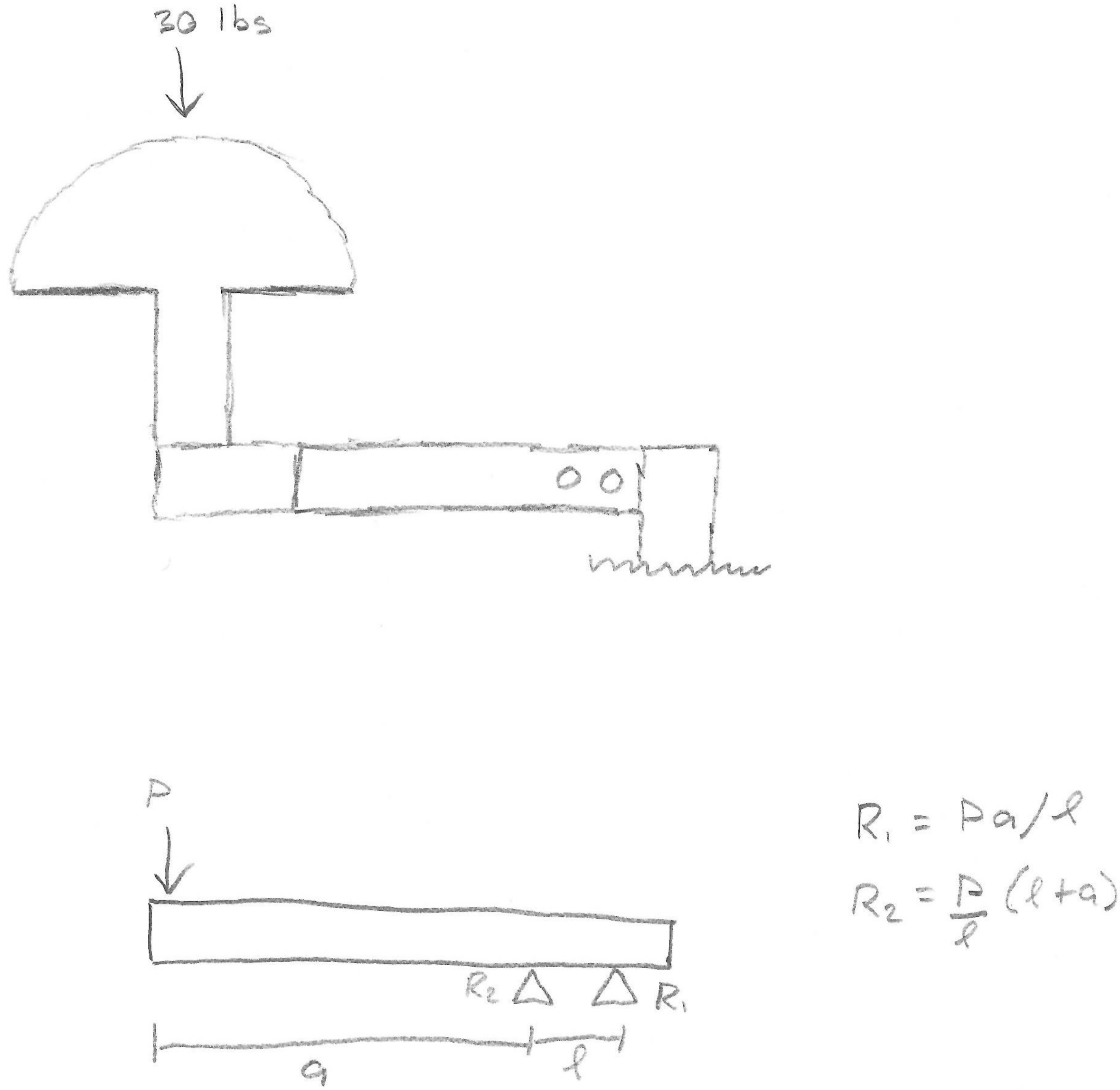


Figure 35: Sketch of FBD on upper half of the bit brace.

Using this model, we were able to determine the reaction loads on the bolt holes of the elbow bracket. We then input these into an FEA model of the part. For the other loads on the bracket, we chose to fix the other bolt holes. This is not wholly representative of the product, however, it is an over-conservative assumption and speeds up simulation time. Below is an image of the stress distribution in the elbow bracket.

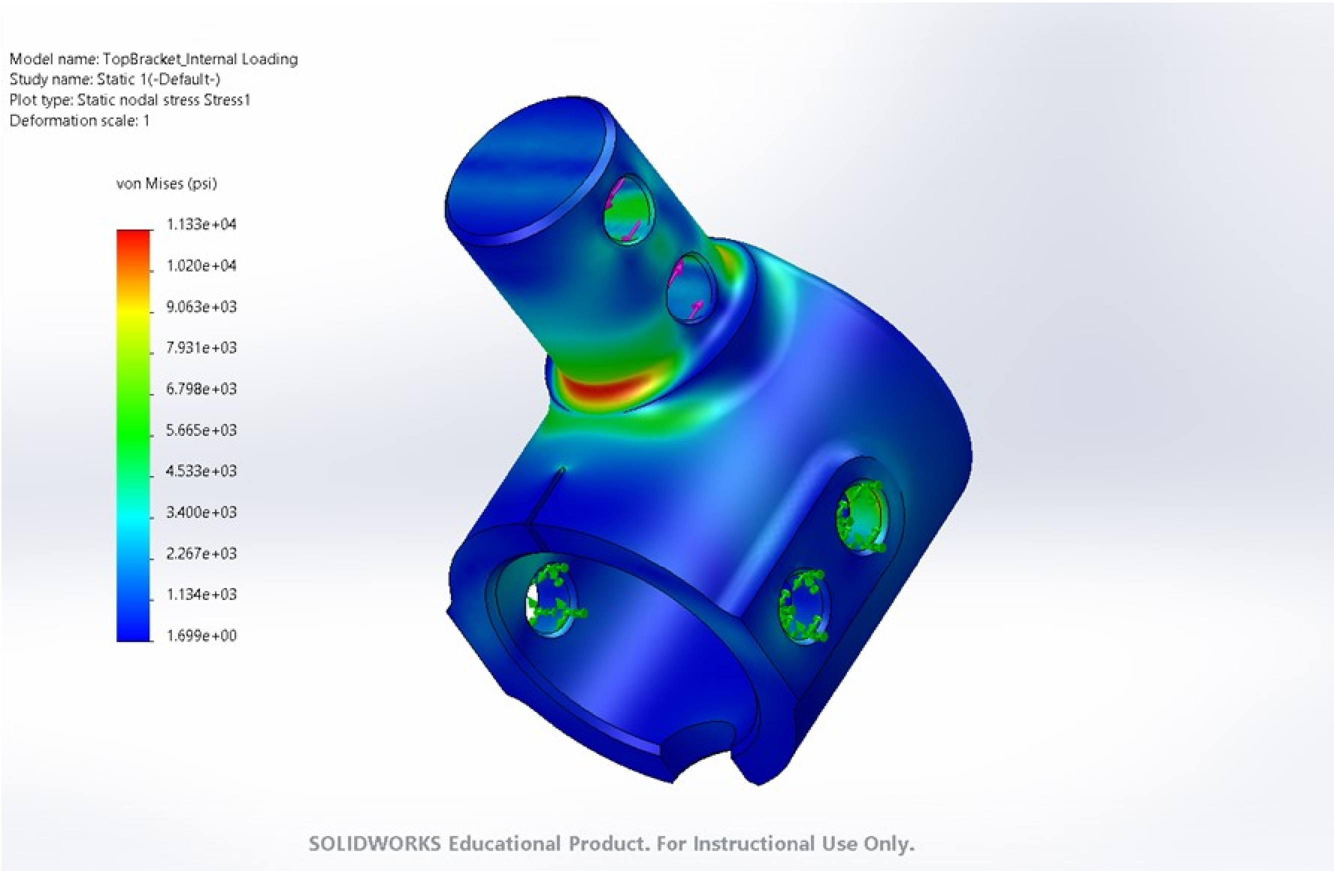


Figure 36: FEA results of the Elbow Bracket

The FEA showed us that the SLA printed part would fail under the reaction forces calculated in the FBD. However it was not feasible for us to increase the material thickness at the failure point, as that would impact the clearances for the bolts used to telescope the brace. In order to prevent the brace from failing, we chose to add steel gussets to the outermost bolt holes to reduce the deflection, and therefore the stress in the elbow bracket. We then chose to rapidly prototype and test this fixture, and no failure was observed under use of the part.

6.1.3 Model Size Limitations

Our primary goal when creating the adjustable bit brace was to be able to scale the bit brace from full size to 1/2 size in the height and rotation of the brace. In order to determine the relative size of the bit brace we used the ratio of the full sized bit brace to determine the desired half sized bit brace, which is given by the following equation.

$$\eta_{want} = \frac{C_{inner}}{C_{outer}} = \frac{r}{R} = \frac{1}{2}$$

However during the design of the brace, we realized that in order to fit all of the fasteners and telescoping tubes, we would not be able to scale the brace down to half size. A section view of the bit brace at its reduced configuration is shown below.

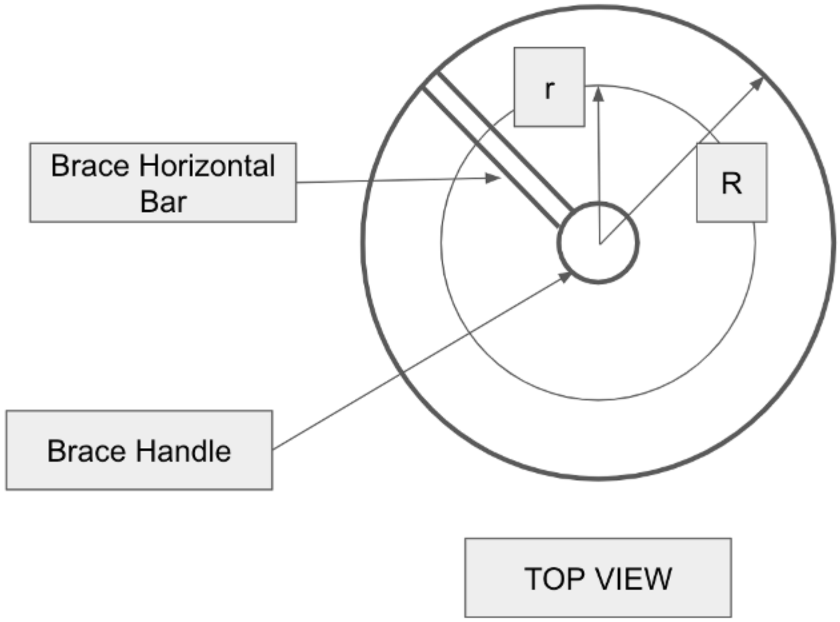


Figure 37: An overhead schematic of the relative radii of rotation

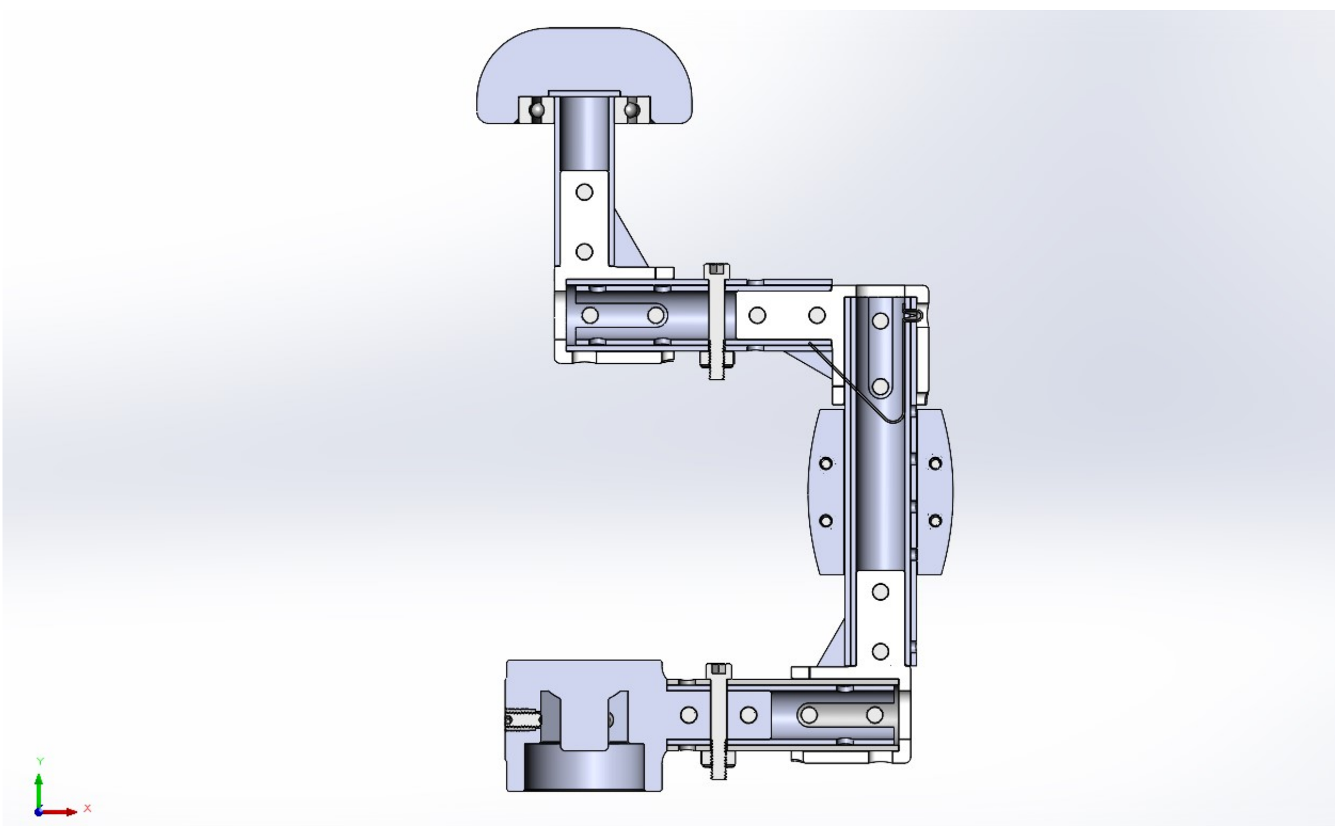


Figure 38: Section View of the 2/3 reduced configuration of the adjustable bit brace

This demonstrates the tight packaging that comes with bolting and fully constraining all of the parts that go into the bit brace prohibits us from achieving our stretch goal of 1/2 size. However, we were able to achieve the needed product specification of 2/3 the original size, which is the reduced configuration.

6.2 Design for Saftey

Every device has some inherent risks associated with operation of the device. These risks could stem from the part failure that can cause harm to the user or damage property of the user. There are also some safety concerns that are not associated with the device failure itself, rather there could be risks involved with components of the device (i.e. small parts with children, shock hazard with electrical equipment, etc). The ABB has many moving parts that can all cause some sort of risk to the user operating the device. The following information describes all of the inherent safety risks for the ABB.

6.2.1 Risk #1: Chuck comes loose

Description: The bit chuck is held in a 3D printed bracket with press-fit screw-to-expands on 2 different sides of the chuck. Through transportation and usage of the device, the screw-to-expands backed out of the 3D printed bracket, causing the chuck to become loose and fall out. This risk could also occur if the plastic bracket begins to crack over long periods of usage.

Severity: The severity for this risk is marginal since it not would not result in a catastrophic failure if it were to happen during normal operation.

Probability: The probability that this risk happens is seldom. The risk does occur but it has only happened once in the last month of using and transporting the ABB.

Mitigating Steps: This risk could be significantly reduced through some minor manufacturing changes in how the chuck is held into the 3D printed bracket. The screw-to-expand clearance holes could be shrunk a little more to allow for a much tighter press-fit and the inserts could be applied with an adhesive that mitigates the risk of them backing out of the hole over time. Additionally, the brace should be inspected before each use to ensure that all of the fasteners are properly installed.

6.2.2 Risk #2: Pinch point on the ratchet

Description: On the exposed ratcheting mechanism there is a small opening where the user can pinch their finger when changing out the bit or removing the bit chuck.

Severity: The severity of this risk is negligible because it is not any different than typical ratcheting mechanism pinch points. It may cause the user minor discomfort, but the user will not have a significant injury from this risk.

Probability: This risk can happen occasionally if the user intends to change the bit frequently during operation, or if the user wants to remove the bit chuck for storage of the ABB.

Mitigating Steps: Some steps to mitigate this would be to include a warning label for the pinching point location to warn the user of the hazard. Also, there could be an additional cover around the area if the severity and probability of this risk are increased over time.

6.2.3 Risk #3: Telescoping tubing failure

Description: During intense operation of the ABB, the telescoping tubing fails causing a collapse of the whole device. With the slot design, the ABB has some extra compliance when in its maximum expanded state.

Severity: This is a catastrophic risk as it could cause significant harm to the user while drilling or screwing something. The failure of the tubing would cause the ABB to collapse with the user applying significant axial forces.

Probability: This risk is unlikely to occur due to the manufacturing of the ABB. Although there is more compliance in the expanded state, the ABB should be able to withstand axial forces that are more than expected.

Mitigating Steps: Some steps towards mitigating this issue are to avoid operating the ABB in is fully expanded form during screwing or drill that requires a lot or force. Another possible step is to increase the telescoping tubing wall thickness to allow for less compliance around the slot gaps in it's expanded form.

6.2.4 Risk #4: Elbow joint failure

Description: 3D printed elbow joints fail under device operation. Due to the axial and tangential loads applied while using the ABB, the 3D printed brackets could become weak and fail during screwing or drilling.

Severity: This is a critical risk as it could cause harm to the user operating the device. The elbow joints hold together the overall frame, so if these parts fail, the overall structure of the ABB would be at risk of collapsing.

Probability: This risk is unlikely to happen as the elbows have been FEA optimized and tested at larger than expected loading conditions.

Mitigating Steps: During initial testing, this risk was very apparent, thus we added additional steel gussets to help distribute the load better through the elbows. If the risk becomes more critical and probable over extended testing, then other mitigating steps could be taken to further support the elbow joint. These other steps could be to add more supporting mechanisms to mitigate failure.

6.2.5 Risk #5: Rotating handles seize

Description: The handles (top and side grip) fail to rotate freely as the ABB is being used. After continued use, the handles could wear out and seize on the tubing, causing the handles to not rotate while the user is rotating the ABB.

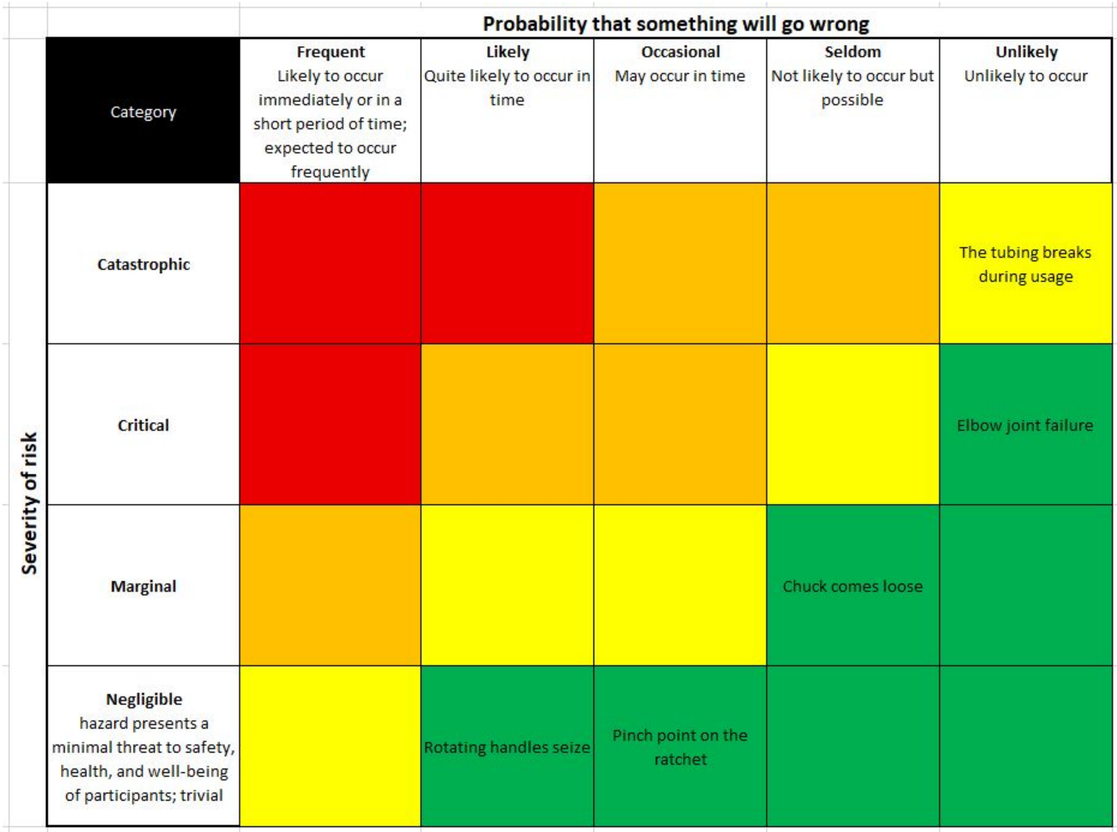
Severity: This is a negligible risk since it is not likely to cause any harm to the user during operation. The user might slip if the handles instantaneously seize, but that would not be much different than if a user's hand slips off the handle

Probability: This problem is likely due to the large number of moving parts around the handles. There is a decent chance that after using the ABB for a while, the 3D printed handles would end up locking up after a great deal of usage.

Mitigating Steps: Some steps to mitigate this would be to incorporate some bearings in the handles that offer much less friction in the handles. The handles themselves could also be re-engineered to offer a better design for mitigating seizing.

6.2.6 Heat Map

The following figure illustrates a heat map of the previous risks that aids in the visualization of the risk assessment. The risks within the green region relate to non-critical risks of the design. The color of the heat map changes from green to yellow to orange to red, indicating increasingly critical risks of the overall design.



Severity of risk	Probability that something will go wrong				
Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Catastrophic					The tubing breaks during usage
Critical					Elbow joint failure
Marginal				Chuck comes loose	
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial		Rotating handles seize	Pinch point on the ratchet		

Figure 39: ABB risk assessment heat map.

From the heat map (Fig. 39) we can prioritize the risks that the ABB presents to the user. The highest priority risk based on the heat map would be the tubing breaking during usage. Even though this risk is highly unlikely, it would cause a lot of harm to the device and the user if it were to occur, thus it it of the highest priority risk for the ABB. The next risk in priority would be an elbow joint failure. Again, this risk is unlikely but the severity of the risk proves to be an issue that has large priority to consider. The chuck coming loose and the handle seizing are tied for the second to last priority since they are not that severe of a risk, but have a decent probability of occurring over time. The risk of the least priority is the pinch point on the ratchet, since is does not occur too often and is negligible in severity. The overall most important risk that needs to be considered in the failure of the frame due to compliance in the frame's telescoping tubing. Future iterations of this device will need to consider this risk and attempt to mitigate it as much as possible.

6.3 Design for Manufacturing

One of the design constraints set by our customer was that the Adjustable Bit Brace could be manufactured and assembled by an experienced at-home maker with access to basic equipment. The group limited that definition to 3D printers, hand saws/bandsaws, sanders/belt sanders, and drills/drill presses.

Total Parts (excl. Fasteners)	35
Count of Fasteners	76
Total	111

The figure below shows only the fasteners in their reduced configuration from within the ABB.

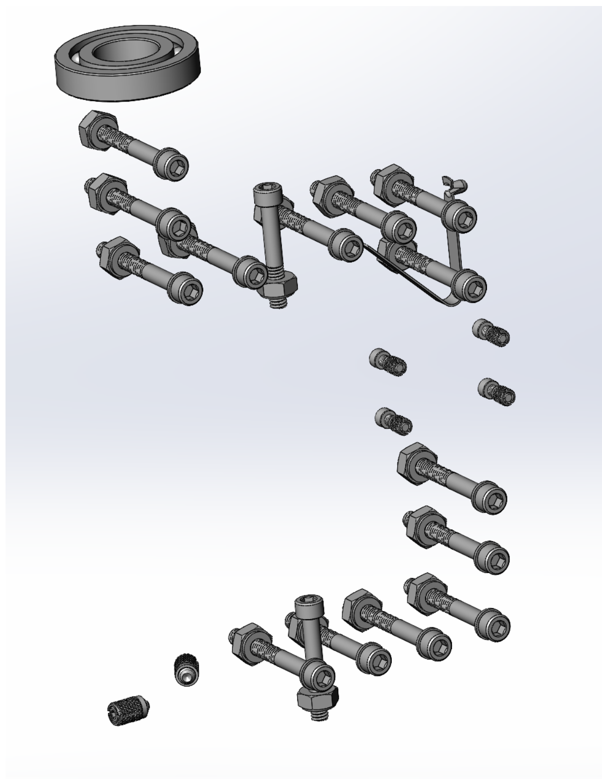


Figure 40: The fasteners and mounting hardware of the ABB isolated

The table below provides a further breakdown of some of those components by specifically highlighting the number of printed parts, fabricated metal parts, and non-threaded hardware such as pin clips and bearings.

Fabricated Parts	14
Printed Parts	11
Non Threaded Joining Hardware (e.g. bearings)	8

Theoretically necessary components (TNCs) are critical components within the design that move, require a specific material, or have a unique service constraint. A few examples of TNCs in the Adjustable Bit Brace are:

- Telescoping Aluminum Tubing

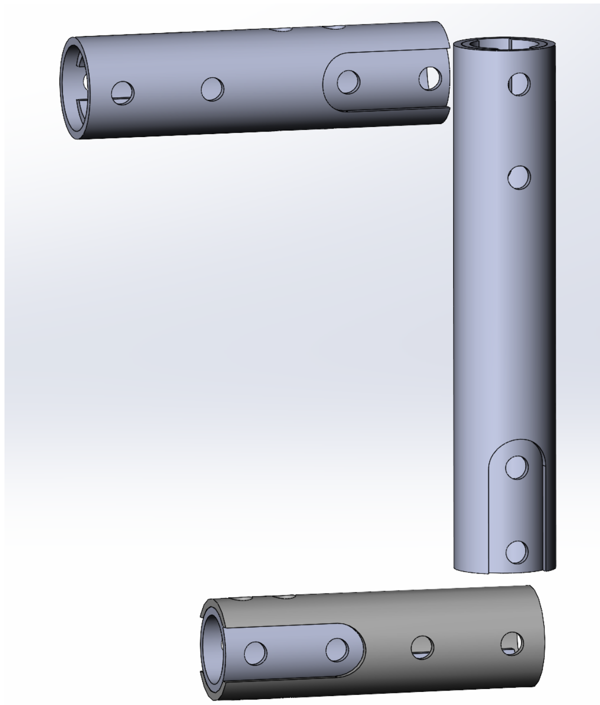


Figure 41: The telescoping tubing isolated

The telescoping aluminum tubes are theoretically necessary components because they move relative to each other during adjustment of the brace from the largest to smallest positions. This feature is a critical user requirement and a performance goal for the ABB. They must be made of aluminum because this tubing is designed to be seamless during manufacturing so that it can be used in a telescoping manner. Different materials were considered, however, plastics are not strong or stiff enough per our Engineering Models and steel is too heavy for practical application. As a result, aluminum was the most conducive material as it is light, strong, stiff, and slides with minimal friction against itself during adjustment.

- 3D Printed Elbow Brackets

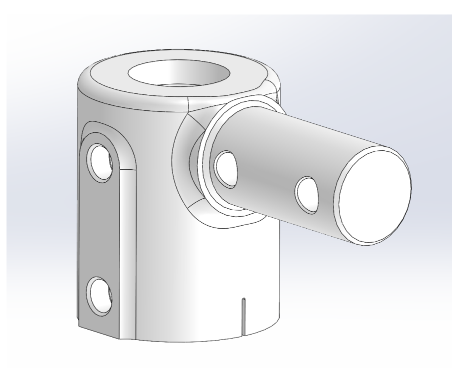


Figure 42: The 3D printed eblow joints

The elbow brackets are 3D printed to maintain their lightness and manufacturability given their complex geometry. These parts are integral to the function of the bit brace because they allow perpendicular telescoping tubes to interconnect where the bit brace needs to change direction. For these to be made of a different material they would have to either be weldable (which would require the tubes to change to an easily weldable material like steel), or multiple components that fastened together. The first change would infringe on other customer needs and the second would decrease the stiffness and ease of assembly of the overall system.

- Ratcheting Square Drive

  The ratcheting square drive component is a necessary component because it ties directly to a customer need and allows the tool to function as a proper bit brace. The user has asked for the brace to be ratcheting and reversible so that it can be used in confined spaces. A replacement for this component would limit the ability to use the brace in tight work spaces and adapt to any tool that the user may want. The square drive is compatible with the user's drill chuck that accepts drill bits, square drives, hex drives, and other bits for a wide range of applications.

- 3D Printed Square Drive Adapter Bracket

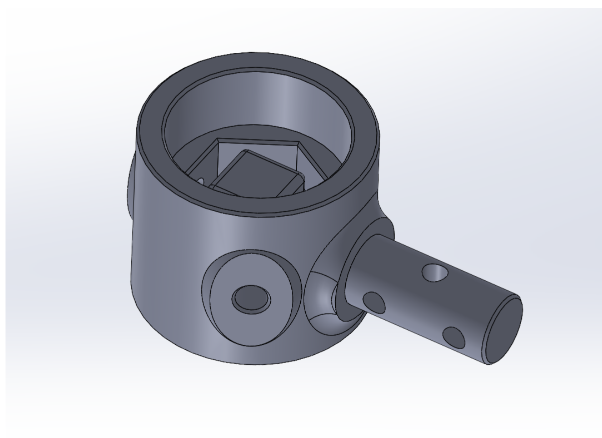


Figure 43: The 3D printed SLA square drive bracket adapter

  The 3D printed lower bracket is a necessary component because it allows the telescoping tubes to change direction for to the vertical ratchet drive and drill chuck. Consequently, this part is printed because it requires a complex geometry to accomplish all of its functions. To be replaced it would need to be CNC-machined or made of several welded constituent components. It is also important that this part is able to connect and disconnect to different ratcheting fixtures and drill chucks to satisfy the customer's needs.

- Aluminum Top Handle Adapter Tube

- Corner Gussets

The components of the Adjustable Bit Brace could be minimized in several ways. First, the elbow brackets documented above in the TNC section could be combined with some of the telescoping tubes so that they are not fastened together but instead homogeneous. This would reduce the fasteners in the elbow brackets and combine the brackets with the tubes. While this is advantageous for simplifying the bill of materials, it would dramatically increase the complexity of fabrication requiring intricate welding or CNC machining to create the composite parts. Additionally, the elbow brackets could be further improved to include either intrinsic pins or fewer pins by changing the fitment with the aluminum tubing. The brackets are designed in their current way to maximize the moment/force reaction of the aluminum tubing, however, some of the fasteners could be removed to simplify assembly. This would not complicate fabrication of these components as they are printed but it would decrease the stiffness and structural integrity of the system. Lastly, the steel gussets could be reduced or removed to simplify the assembly. This could be done by either reducing the number of gussets in half (by only attaching them on one side instead of both), or changing the material of the gussets to an aluminum or printed material. Further testing and analysis would need to be done to ensure that the user's loading assumptions are correct, the brace is following the team's intended load paths, and that those replacement materials are significantly strong, stiff, and fatigue-proof for integration.

6.4 Design for Usability

The adjustable bit brace was designed for comfort and usability by referencing and testing a commercial bit brace. The following factors were identified as being important for a comfortable and user friendly bit brace:

- The top handle should be comfortable to grip and should rotate freely with little resistance.

  The top handle is a curved shape in order to create an ergonomic grip for the user. Additionally, the bottom face of the top handle is filleted so the user is not gripping a sharp corner while using the ABB. In the initial prototype, the top handle was installed on the top vertical tube with only a shoulder bushing. The resulting rotation was smooth, but there was a fair bit of resistance to rotation which was not conducive to comfortable operation. Therefore, a ball bearing is installed between the top handle and the tube on which it rests to ensure the smoothest possible rotation.

- The middle handle should rotate freely with little resistance.

  The scaling vertical size of the bit brace made the creation of a vertical grip more challenging. Initial prototypes had two handles that could be interchanged depending on the configuration being used. These early prototypes relied on using the protruding section of the button clip to constrain the axial movement of the handle. However, this solution was determined to be awkward and not user-friendly. Therefore, the final prototype has a single handle that fits on the ABB in all configurations. The handle rotates freely, and the axial movement is not constrained as this was determined to not be a major factor in usability.

- There should be minimal vertical deflection when the user applies a downwards load of approximately 30 lbs.

  The stiffness of a bit brace is a major factor in how comfortable it is to operate. Therefore, it was determined that minimizing the deflection of the prototype during operation would maximize the user's comfort. To minimize the compliance, steel gussets were added to the corners to support the 3D printed components. Additionally, it was ensured that even at the largest configuration the telescoping tubes had enough overlapping material that the ABB stayed stiff.

7 Final Prototype

7.1 Final Validation Testing

Several tests were run on the final prototype as it was being fully assembled. This included determining the final weight of the assembly and measuring the strength capabilities and deflection performance at different sizes in accordance with the team's performance goals. Figure 44 shows the final weight of the ABB. With all fasteners attached but the after-market drill chuck removed, the part weighs 0.45 lbs.

Figure 44: The ABB being weighed after final assembly

Next, pressure was applied to the brace while positioned in a scale. Two different procedures were run using the test setup shown in figure 45. First, the brace was evaluated to determine its ultimate load carrying capabilities. This test was run twice: the first time it failed at 44 lbs and after being reassembled it survived to 45 lbs. As per the performance goal definitions above, the desired outcome saw the bit brace surviving 30 lbs of axial load while the ideal condition withstands 45 lbs.

Figure 45: The ABB being held for strength testing after starting a hole into a wood block

Figure 46 shows the digital readout on the scale while performing the axial strength test.

Figure 46: The scale readout as the ABB was tested up to and held at 45 lbs of downward force

Figure 47 shows the failed part under the first 44 lbs axial test. The brace failed at one of the SLA printed elbow joints.

Figure 47: The broken SLA printed elbow joint during one of the proof load tests

The second test included a tape measure behind the brace to measure the deflection. This was conducted at both the extended and condensed configurations. The performance goals outlined deflection targets of 0.1” under 30 lbs of force. The fully extended configuration presented around 0.2” of deflection under 30 lbs of downward force. The fully condensed configuration saw much less than 0.1" of deflection. It was again determined that 30 lbs of force was far greater than a typical operating load so the deflection load target was too high. Moreover, after final assembly it was found that the fully extended bit brace was larger than a standard off-the-shelf brace that the deflection target was based on.

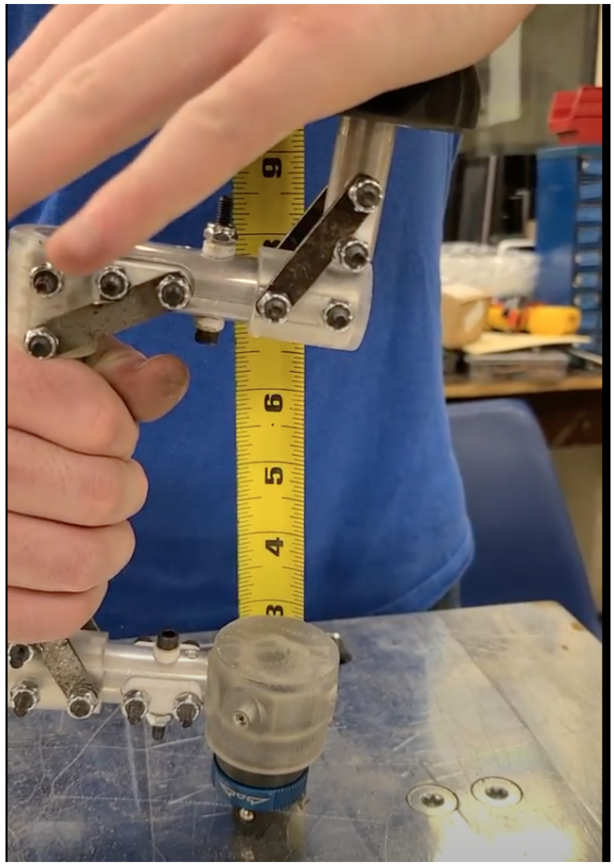


Figure 48: The deflection test configuration where the drill chuck was removed and the brace was loaded on a scale with a tape measure in the background

Figure 49 shows the testing procedure to measure the tangential testing of the brace. The performance goal states that the brace should be able to withstand 15 lbs of radial load. The brace was tested by holding down the extrema and applying an upward load via a hanging scale. The brace survived to over 12 lbs of force but was not tested up to 15 lbs. During preliminary functionality testing, it was determined that 15 lbs was not a realistic operating load.

Figure 49: The ABB undergoing the radial load test

7.2 Assembled Prototype

The final bit brace was assembled and tested to ensure that as many of the customer needs surrounding successful operation were met. The brace was assembled in its largest, smallest, and an intermediary configuration and used to drill holes into wood blocks. Figure 50 shows the ABB assembled in its expanded vertical configuration with a drill chuck attached to a ratcheting insert and a 1/4" drill bit.

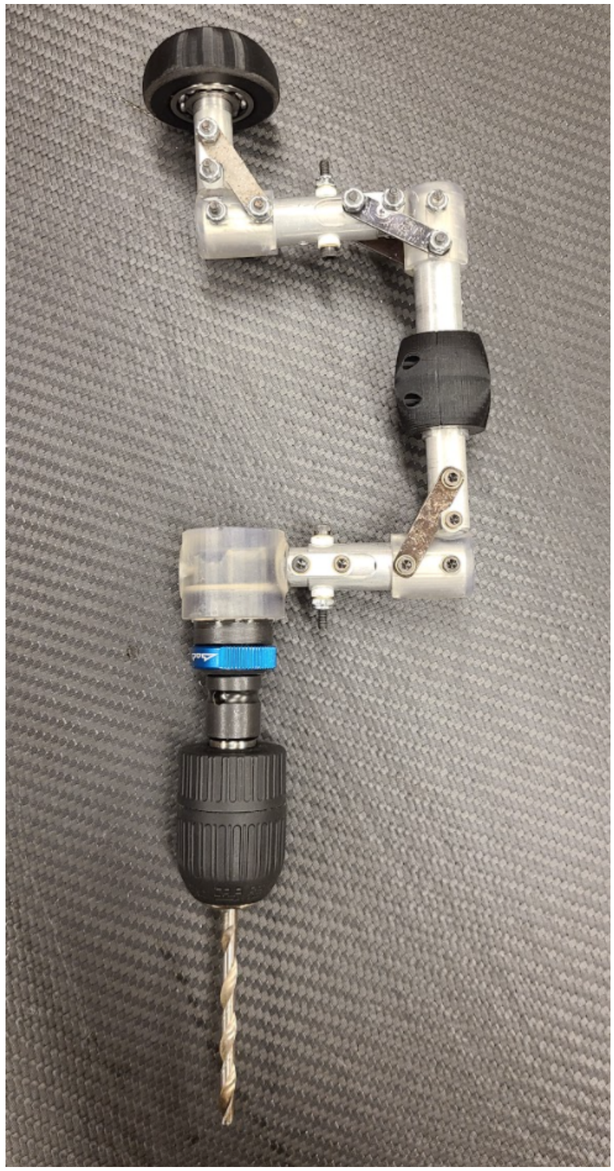


Figure 50: The ABB in its final assembled form. In this configuration, the radial adjustment is at its smallest and the vertical adjustment is at its largest

Figure 51 shows the bit brace in its smallest vertical configuration but a larger radial station.

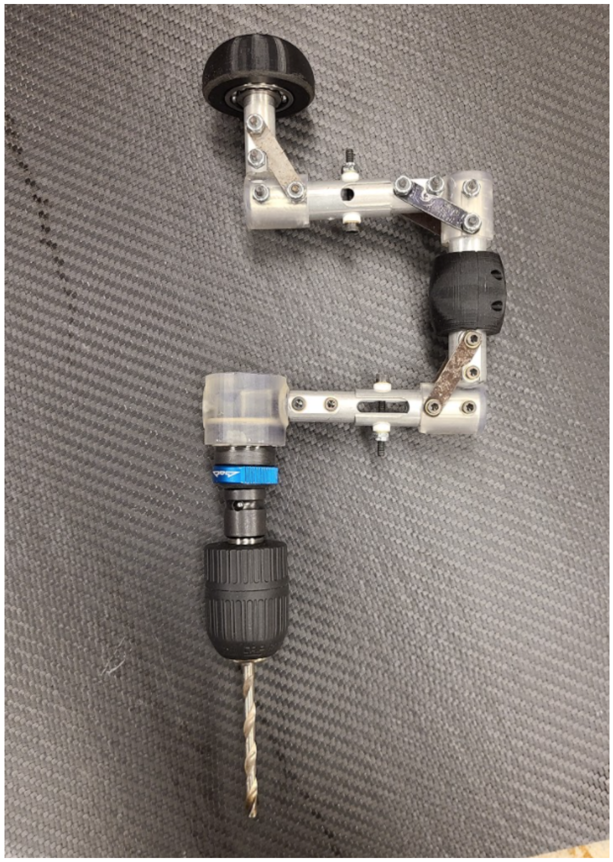


Figure 51: The ABB configured so that the vertical adjustment is at its smallest but the radial is at the largest

Figure 52 shows the ABB in its smallest configuration where the radial and vertical adjustments are both full contracted.

Figure 52: The ABB entirely contracted to 2/3 of the original size

Figure 53 shows the bit brace in its largest configuration in both dimensions.

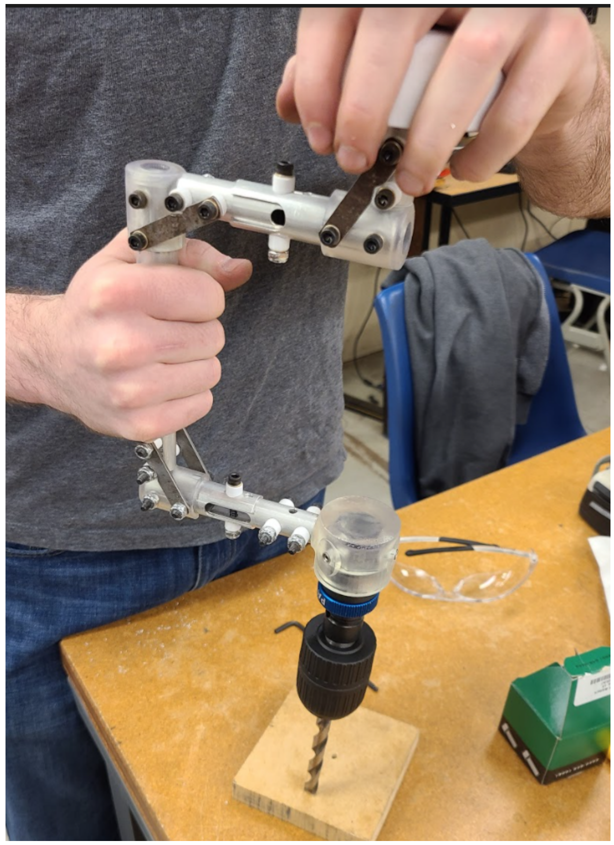


Figure 53: The ABB at its largest, full sized configuration

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